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Brassica biodiesels: Past, present and future

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ABSTRACT

Essential sustainability requirements for biodiesel are that the product should be truly renewable and have a lower negative environmental impact than fossil fuels based on the latest insights. Biodiesel is not a most sustainable product in all geographical circumstances. This survey paper reviews the performance and prospects of rape biodiesel production on a global basis using some 40 life cycle assessments (LCAs). The paper identifies best (agricultural) practice and laggards. Life cycle energy balance depends on specific climatic conditions, and the agro- and processing technologies used. Alternative oilcrop cultivation practices and technologies were assessed. Opportunities to improve rape biodiesel life cycle energy efficiency and environmental impact by implementing new technologies in agriculture as well as in industrial processing have been identified for various Brassica oilcrop cultivars in relevant production areas. The consequences of large-scale renewable energy action plans have been considered. Improvements are needed for rape biodiesel to stay in business. The paper concludes with perspectives and recommendations.

Contents

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1. Introduction

Three main renewable energy chains can be identified: biomass, bioethanol and biodiesel (BD). Mankind needs liquid fuels. Liquid fuels, mainly bioethanol, biodiesel, and eventually biobutanol provide one of the few options for (partial) fossil fuel replacement in the short- to medium-term. Although biofuels (58.9 Mtoe) only account for about 0.5% of global primary energy consumption, world biofuels production grew by 13.8% in 2010. Biodiesel (26%) is the dominant product in Europe and Asia and bioethanol (74%) in the Americas.

Biodiesel has the potential to offer both greenhouse gas (GHG) savings and increased energy security. At the same time, there are concerns regarding reported poor energy balances, ecosystem destruction, land displacement issues [1] and interferences with food supplies [2]. Some advanced technologies (such as bioethanol from agricultural or forestry residues) or FT diesel (from wood) have the potential to produce biofuels with higher GHG savings (*cfr.* Table 30), but are currently still immature and expensive (no significant market penetration before 2020). Wastes and algae do not require agricultural land.

Biodiesel (fatty acid methyl esters) raises wide interest because of a series of perceived benefits: political and economical (national energy security, trade balance); agricultural (rural development); environmental (renewable, biodegradable, and non-ecotoxic; GHG mitigation); fuel system lubricity (favourable ester lubricity properties); health (less harmful exhaust emissions); and ease of use and safety (high flash point). Oilseed esters are much more biodegradable ($>95\%$) than mineral oils (25–40%) and pollute less than conventional diesel (CD) as far as sulphur oxide, particulates, and aromatic hydrocarbons in GHGs are concerned. It should be remembered that the transportation sector is an important contributor to overall GHG emissions (27.4% in Europe, about 20% worldwide) [3]. Other notorious (stationary) sources of GHG emitters are power plants (2324 Mt CO_2 eq/yr, 72%), petroleum refineries (183 Mt CO_2 eq/yr, 5.7%) and the chemical industry (175 Mt CO_2 eq/yr, 5.4%).

In addition to ignition quality (cetane number), several other properties are important for determining the suitability of biodiesel as a fuel, namely heat of combustion, pour point, cloud point, and (kinematic) viscosity [4]. Some problems with biodiesel use are slightly increased NO_X exhaust emissions [5], oxidative stability, cold-flow properties and higher price. Biodiesel is miscible with conventional diesel in all ratios and can be used in diesel engines without significant engine modifications. Blends with petrodiesel are denoted by acronyms such as B20, which indicates petrodiesel extended with 20% biodiesel.

Until 2005 biodiesel was conceived largely in the context of local agroclimatic conditions or national fuel needs, but has emerged more recently as a global industry and commodity. Since its inception in the early 1990 s the biodiesel market has been characterised by rapid growth (especially in Europe) until 2007 but by restrained growth afterwards. Global biodiesel production (2010) was about 16.1 Mt (Europe 9.5 Mt, USA 1.1 Mt, Argentina and Brazil 3.8 Mt, ROW 1.7 Mt), which was mainly derived from rapeseed oil (47%), soybean oil (35%), palm oil (10%), (high-oleic) sunflower oil (4%) and other oils and fats (including tallow, waste oils and corn oil) (4%). International biodiesel trade streams amounted to 2.25 Mt in 2010 [6].

The amount of biodiesel to be produced is very much a political issue, is imposed by governmental mandates, encouraged by subsidies, and does not really depend on free market trends. In May 2003, the European Union has issued the Biofuels Directive (2003/30/EC) with a specific EU-wide obligation of 5.75% (by energy) or about 18.0 Mt/yr of biofuels for the transport sector by 2010. Biodiesel production has seen rapid growth in Europe (from 300 kt in 1998 to 9.5 Mt in 2010). EU is the leading biodiesel producing and using region worldwide, representing about 60% of global output. In 2009, biodiesel accounted for about 80% of biofuels produced in Europe (bioethanol 20%). Although the EU target of 5.75% by energy (7.1 vol.%) has not been reached (short of 2.1 vol.%), an even more ambitious EU biofuels target of 10% by energy has been set for 2020 in the latest Renewable Energy Directive 2009/28/EC (RED) [7]. There are serious doubts about its feasibility in terms of sustainability. Many governments have already revised their biofuels policy. Ireland has lowered the 2010 biofuels target from 5.75% to 3%, citing price and emission concerns. UK's Renewable Fuels Agency (RFA) has recently proposed that the Renewable Transport Fuels Obligation (RTFO) target for 2008/2009 (2.5 vol.%) should be retained, although with a reduced rate of increase in biofuels of 0.5 vol.%/yr rising to a maximum of 5 vol.% by 2013/2014 [8]. RFA has recommended in vain that the EU slows down its advancement of biofuels. Expanded oilseed production is limited by the availability of cropland.

Biodiesel is now also the fastest growing alternative fuel in the U.S., with production soaring from 2 Mg in 2000 to over 1000 Mg at present (approximately 25.5 million barrels) despite the fact that diesel use in the USA is very limited. EPA has extended its renewable fuels standard (RFS2) volumetric compliance level from 500 Mgy in 2009 to 1 Bgy by 2012, a target that thus has already been hit in 2011. At the same time, biodiesel nameplate capacity has even grown abnormally (up to 21.9 Mt/yr in Europe 2010; 3.0 Bg in USA) and currently determines largely underutilized capacities and idle plants. Despite rapidly expanding nameplate capacity worldwide use of biodiesel remains marginal. The EU production in 2009 (9.0 Mt) represents 4.5% of diesel use in Europe. The US production in 2011 (>1000 Mg) accounts for at most 1.7% of diesel use (238 GL/yr, 2006). In Canada, biodiesel production was only about 0.1 GL/yr in 2006, compared with petroleum diesel use of about 28 GL/yr (2006).

A recent OECD-FAO forecast sets global biodiesel production by 2020 at 29 Mt [9]. An OECD recommendation [10] urges countries to end mandates for biofuel production and replace them with technologically neutral policies, such as carbon taxes that stimulate energy efficiency and a broad range of approaches to reduce GHG emissions (certification requirement). Indiscriminately increasing the amount of biofuels may not automatically lead to the best reductions in emissions [11]. Recently, also concerns have been expressed on large biofuel mandates on account of previously ignored increased GHGs through emissions from land-use change [1]. Indirect land-use changes are indeed a valid concern even though the degree of uncertainty regarding their magnitude is considerable. A regulations rethink is necessary.

Energetic use of biomass offers numerous benefits but also ecological drawbacks. For instance, agricultural production of biomass is relatively land intensive, and also partly involves higher transport costs than fossil fuels. There are risks connected with pollution and there is the danger of reducing biodiversity if biomass is cultivated in monocultures. If biomass is used for energy purposes, then the ecological advantages must exceed the negative impacts on human life and the natural environment. Potential environmental and social impacts that could be produced in tropical countries by large monocultures of oilseeds include deforestation, reduction of wild biodiversity, soil erosion, water overuse and contamination. Other major hindrances to market penetration of biofuels lie in the infrastructure to move feedstock, biofuels, and fuel blends.

Transport is the only sector that has seen its emissions increase over the past two decades. The EU's Fuel Quality Directive (FQD) aims at reducing transport fuel emissions by 6% by 2020 [12]. Biodiesel has been advocated as a partial solution to the increased atmospheric CO_2 concentrations because the carbon in biodiesel is recycled [13]. Biodiesel has the potential to deliver significant environmental benefits although there is little consensus on the degree of sustainability for various cultivation practices. Clearly, to reduce overall GHG emissions, the emissions of all GHGs required to produce, transport, and process the biodiesel crop must be less than emissions from fossil fuels displaced by the biodiesel. The public will ultimately reject biodiesel if it is not perceived as a credible environmental alternative to fossil fuel (*cfr*. Table 29). Both good and bad biodiesel products exist, not only in terms of economic profitability but depending on energy balance and environmental sustainability. As the number of scientific papers, reviews and other publications reporting possible environmental merits and risks of biodiesel fuels is staggering, it has become increasingly more difficult to have clear insights in the many interrelated factors and best options available for future development. Most recently, the uncertainty on the overall assessment of this complex subject is growing.

The net benefits of biodiesel production from energetic, environmental, GHG, and socio-economic perspectives are still widely debated [1,8,11,14–18]. Certain conditions are inductive to a negative energy balance for rape biodiesel [19], most others have determined net positive energy balances [15,17]. Studies showing positive balances generally assume current agricultural production technologies, resulting in higher yields, lower energy inputs in crop production (*e.g.* reduced tillage, more efficient fertiliser management). New technologies for oil extraction could further reduce energy requirements [20].

Low-carbon fuel policies such as the EU RED and the UK RTFO have included minimal sustainability criteria to govern the production of biofuels. Consequently, it is timely to reconsider the sustainability of various manufacturing routes based on best agricultural practice and production technology. In particular, it is an objective of this paper to gain insight in the future prospects of rape biodiesel – the main biodiesel worldwide – in a global energy system. Quantification of the net impacts of various feedstocks by tools such as whole-life-cycle-assessments (LCAs) from field to fuel use provides a powerful means of determining the relative benefits of one production pathway over another and of biodiesel as an alternative transport fuel to fossil diesel, even though various uncertainties still exist in these approaches [21]. In this paper we have compared a multitude of very recent LCAs of rape biodiesel (*cfr*. Table 4), referring to different agricultural and industrial contexts with broad geographical coverage (both European and extra-European conditions). Additional objectives are to identify the most important environmental loads and effective parameters in rape biodiesel life cycle systems and to suggest measures for improvement. Conclusions are drawn and recommendations are formulated on the basis of current best practice. The results of LCA studies can be used to improve the performance of laggards in agricultural and manufacturing practices and as an input to the strategic decision-making process for future transport energy policy.

The currently available studies show considerable bandwidths of the potentials, environmental impacts and costs of rape biodiesel. This makes an objective assessment difficult and a discussion potentially controversial. Occasional comparisons will be made with other biofuels but this is essentially not within the scope of this paper. It should be remembered, however that most energy crops such as wheat, corn, rapeseed, soybean and sunflower are highly substitutable. In particular, vegetable oil markets are highly integrated. This paper has adopted a wide perspective with particular attention being devoted to the potential impacts of growth of demand and the feasibility of large-scale biodiesel production. Land-use changes and imports are consequences to overcome domestic production constraints.

2. Biodiesel feedstock

There are two major markets for vegetable oils, 81% food and 19% industrial uses including biodiesel. World oilseeds production is expected to increase by 23% from 413 Mt in 2010/2011 to 507 Mt in 2020/2021, for 67% in the developing world (mainly Brazil, India and China) [9]. Global vegetable oil production will increase by over 30% from 138 Mt to 180 Mt (and from 45.7 to 65.8 Mt for palm oil). The main driver for expansion is the demand for edible oils for the food market. Food use will increase from 113 Mt to 147 Mt and biodiesel from 18.4 Mt to 26.8 Mt [9]. By 2020, biodiesel production accounts for 16% of total oil consumption compared to 10% in the 2008–2010 period. Vegetable oil use for biodiesel production will reach about 50% of the EU's total domestic consumption, as compared to 37% in 2008–2010.

The choice of feedstocks for biodiesel is determined by a variety of factors including economics, local markets, predominant climate and infrastructure as well as by political priorities. Feedstock represents the main factor (up to 80%) for cost evaluation of biodiesel. Industrial-scale biodiesel production is primarily of interest to oilseed producing areas, less so for vegetable oil importing countries. European biodiesel production is largely from refined rapeseed oil ($<0.5\%$ free fatty acids) since the crop can be cultivated in cool, temperate conditions; other oil-producing crops require warmer climates.

Biodiesel feedstocks are regionally highly diversified. In Europe, only rapeseed, sunflower and soybean are candidates for cultivation for energy use. Average yields in European countries show variability depending on genotype, growing techniques, environmental conditions, type of soil and input intensity levels. Up to 2008 the EU Common Agricultural Policy (CAP) included compulsory set-aside regulations which allowed for growing of new and traditional crops for non-food industrial end-uses with full hectare premium (EC Directive 1870/95). In Germany it is practically only possible to cultivate bioenergy crops on such set-aside areas. Rape and sunflower could be grown on set-aside land all over the EU and are the two most promising species for further development in Europe. Soybean is a protein-oilseed crop that, because of the high protein content commonly used for animal feed, had not been included in set-aside land in EU countries. These biodiesel crops have been cultivated for a long time for food oil (and soybean protein) production and the growing, hauling, storing and oil extraction techniques are well established. The effective yields from set-aside cultivations (4 Mha in 2007 out of 109 Mha of arable land) are generally lower than EU average.

The set-aside mechanism was abolished in 2008. EU27 2011/2012 produces 29.44 MMT oilseeds (20.82 MMT rapeseed, 7.00 MMT sunflower, 1.16 MMT soybeans and 0.46 MMT cottonseed) and imports 15.0 MMT [22].

Rapeseed, sunflower, palm (imported) and olive oil are the most important commercial oils for food use in the EU and account for 22.9%, 25.0%, 21.6% and 15.7%, respectively, in 2011/2012 [22]. Of the EU25 supply in 2004 only 0.9% RSO was imported, whilst 100% of the supply of palm oil was imported (largely through Rotterdam). Recently, also growing amounts of soybean oil (as well as soy biodiesel) have been imported. At present, feedstock for an average European biodiesel plant consists of 77.1% rapeseed oil (RSO), 12.8% soybean oil (SBO), 8.4% palm oil (PMO), and 1.7% sunflower oil (SNO) and waste oils such as tallow (TLW) and used cooking oils (UCO). Increased focus on biodiesel in the EU will accelerate vegetable oil demand. EU production of oilseed does not follow the increase in biodiesel production and domestic demand. European biodiesel from current total oilseed production is lame. In order to meet both industrial and traditional vegetable oil demand, EU imports should rise by 42% in the 2011–2020 period [9]. While feedstock (or biodiesel) can be imported into the EU, this will raise costs and contribute to transport energy consumption and emissions.

The market potential of biodiesel originating from currently available agricultural feedstock is limited because of tight supply base and high (overall) production costs. In many countries it is probably not feasible to greatly intensify production of oilseed crops, the expansion of which has implications for a loss of biodiversity.

2.1. Oilseed rape

World rapeseed (crush) production amounts to 59.4 Mt (forecast 2011) [23]. Global rapeseed oil production of 23.4 Mt (2011 forecast) has shown an average growth rate of 4.8%, or 0.52 Mt/yr, from 1987 to 2007. Main producers (2011 forecast) are EU27 (8.9 Mt), China (5.4 Mt), Canada (2.8 Mt) and India (2.3 Mt) [23]. Biodiesel production is the major use of RSO in EU 27; in 2011/2012 6.5 Mt (or 63%) of total rapeseed oil supply in EU 27 is expected to be used for biodiesel [22]. At global level only 16% of vegetable oil consumption is destined to biodiesel production in 2020 [9]. In the past, most of EU biodiesel was produced from domestically grown rapeseed, a relatively highly priced feedstock, but now EU is a net importer of rapeseed. The European Union is the region in the world that is predicted to face the largest annual increase in rapeseed production in the 2005–2015 period [24]. Only 10% of RSO production is exported to the world market, mainly from Canada (80%) and India, mostly to the EU (0.73 Mt in 2007). In recent years, imports in rapeseed and rape oil have also come from the Ukraine [25,26]. Rapeseed oil is a very volatile market [27]. RSO is used for food and industrial applications (13.5 and 5.1 Mt, respectively in 2008). The use for food applications is rather stable with the main growth being in industrial applications since 2003 (notably biodiesel in Europe). Oilseed rape is bred for its nutritional rather than energy content, and only a small part of the plant is used for biodiesel production. This means that the process is not very energy efficient [28].

Rapeseed cultivation 2011/2012 extends to 6.82 Mha of better quality land out of the total EU27 oilseeds area of 11.5 Mha [22]. Rape can be grown over a wide area of North-Central Europe and in some Southern areas where it is planted in full rotation with wheat. Main European rapeseed producers are France, Germany, Poland and UK. Rapeseed oil production in EU25 has increased sharply from 4.3 Mt (2004) to 8.1 Mt (2008/2009). The average yield of European rapeseed is ~3 t/ha; about 38.5% of this yield can be obtained as oil and ~54% as meal. National average grain energy outputs are extremely variable, *e.g.* 78 GJ/ha in France and 14 GJ/ha in less favourable conditions in Belarus. Yields projections for rapeseed 2020 are given in Table 1. Winter oilseed rape (*Brassica napus* L.) is dominant in Germany, being cultivated on 1.23 Mha (UFOP, 2004). Nearly one-third of it is used for non-food production. Germany realises an average yield of 4.1 t/ha rapeseed. Swedish rapeseed is grown mainly as winter rape in Skåne (S. Sweden), in crop rotation mode on soils dominated by boulder clays with a high content of nutrients and limestone. East Anglia (UK) presents similar conditions [30]. The EU default value for lime for rapeseed cultivation is 6.1 kg/t rapeseed. Crop rotation is a common practice [15,31–35]. Rotational set-aside land within a crop rotation is currently used as standard in an agricultural reference system for biodiesel rapeseed production. In Germany and UK planting of rapeseed is restricted to once every 3–5 years to avoid club root and other Brassica diseases [15,32]. Rapeseed is mostly grown in non-irrigated soils under conventional or no-tillage conditions [31,36–38]. The practice of minimum tillage (as usual in the UK and Canada) is beneficial as (i) soil nutrients are stabilised, leading to higher quality soils; (ii) the structure of the soil is improved by the activity of earthworms; and (iii) use of diesel fuel to run agricultural machinery is reduced [30].

Table 1
Yield projections for rapeseed 2020.

Geographic area	Yield (t/ha)	Geographic area	Yield (t/ha)
EU27	3.9	Rest of OECD[b]	2.4
Brazil	3.5	ROW	2.6
China	2.5	SSA[c]	1.9
CIS	1.9	USA	2.7
LAC[a]	2.6	World	2.8

After Ref. [29].

[a] Other Latin American countries (incl. Argentina).
[b] Incl. Canada and Australia.
[c] Sub Saharan Africa.

B. napus is by far the most common rapeseed cultivated in continental Europe. Ethiopian mustard (*Brassica carinata*) is better adapted and more productive in adverse conditions and under low input cropping system when compared with *B. napus*. *B. carinata* shows better agronomic performances in areas with a semi-arid temperate climate such as California and the Mediterranean basin [39]. The oilseed crop, which originated in Ethiopia and is capable of self-adapting to adverse agro-pedoclimatic conditions, allows use of set-aside lands in (high heat and drought) environmental conditions (Spain, Italy), unfavourable for the cultivation of *B. napus*. *B. carinata* provides greater grain yields than *B. napus* in conditions of low rainfall during the grain filling period and high temperature. Canola-quality *B. carinata* is a potential oilseed crop for the Canadian prairies. Limitations of *B. carinata* for biodiesel production are its high contents of erucic acid (33–46%) and linolenic acid (10–16%) (exceeding the EN 14214 limit).

Canola (CANadian Oil Low Acid, a trademark term) is a product of traditional plant breeding techniques to remove the antinutritional components erucic acid and glucosinolates from rapeseed to make the product absolutely safe for human and animal consumption. Canola oil should contain less than 2% erucic acid (C22:1) and the non-oil portion of the seed should have less than 30 μmol of glucosinolates. Increased canola production in Canada since 1965 (11.8 Mt from 6.47 Mha in 2009 with a target of 15 Mt by 2015) has not been the result of increased agricultural area, but rather the better and more sustainable use of the existing land base (summerfallow area). About 90% of canola produced in Canada is now genetically modified, including varieties with herbicide resistance and hybrids. Hybrids are not necessarily transgenic varieties. Hybrid seeds show a higher nitrogen utilisation efficiency

and have higher yields than open pollinated varieties. The adoption of hybrids is one of the reasons for the rapid increase in yields in the past decade. Oil content in canola seed now averages 42.8%, or 2.25 times the oil extraction rate of soybeans. Production of 1 l of canola oil requires 2.15 kg seed.

Two scenarios of crop management are possible, extensive and intensive. In extensive agriculture input levels are low, the limiting feature is low yields and the energy gain may be increased by reducing the energy costs. Intensive agriculture is more practicable when available surface area is limited. In the latter case, high yields associated with high levels of both agronomic inputs and costs may be expected. Careful agronomic management, especially nitrogen fertilisation, must be applied to avoid nitrate leaching. The root system is a key factor in maximising nitrogen uptake [40]; German practice adds on average 165 kg fixed N per hectare of harvested rapeseed. The EU Nitrates Directive limits application of nitrogen-containing fertilisers and manures to 170 kg N/ha/yr [41,42]. The impact on the environment of cultivating rapeseed may be limited by choosing the right cultivar. For rapeseed, an increase in yield seems possible by using new hybrids. Although high yields are usually required to achieve high yields, rapeseed is able to tolerate reduction of inputs without leading to important yield losses, thus allowing optimisation of cultivation techniques with consequent energy savings (especially as regards fertilisation and tillage). The good adaptability of rapeseed to low inputs fits the requirements of both production of biodiesel and low environmental impact. Rapeseed is the fourth most important GMO crop [43].

3. Biodiesel life cycle

A complete life cycle of biodiesel comprises an agricultural stage, oil milling, oil extraction and refining, as well as transportation of the feedstock. The industrial stage consists of pretreatment (optional), vegetable oil (trans)esterification and biodiesel transport to the pump. The fuel stage consists in combustion.

At first glance, biodiesel is generally considered to be environmentally friendly. However, the environmental impacts connected with the production of agricultural raw materials (*e.g.* fertilisers, pesticides, water footprint, contamination of ground and surface water) do not occur in the case of fossil fuels. A whole life cycle assessment (LCA) of biodiesel from production of the biomass *via* conversion to end use as an energy source is needed in order to gain better insight in this matter. At a closer look, the aforementioned benefits of biodiesel are indeed not crystal clear. In fact, production of biodiesel generally takes a significant amount of non-renewable energy: fossil fuel needed for machinery in both the agricultural and industrial phase, as well as for transportation of raw materials, inputs and distribution of biofuel for final use, and embedded energy in chemicals (fertilisers, agrochemicals, methanol). Also biomass processing (crushing, extraction) requires considerable amounts of fossil fuels. The amount of fossil energy used for biodiesel must be measured over the entire life cycle of biodiesel production to determine the extent to which the fuel is renewable. Table 2 summarises the performance indicators of the biodiesel production system from rapeseed. In the geographical areas where the key driver for investment in biodiesel is environmental (*e.g.* in Europe), considerable emphasis is placed on assessing the whole-life-cycle carbon costs of biodiesel production technologies. Typical LCAs assign biofuels the gross benefit of using land, while they should only assign a net benefit. Different LCA studies disagree on the greenhouse gas (GHG) balance of a variety of biodiesel cropping systems, even in the absence of land-use change emissions (*cfr.* Section 6.3.2). The GHG or carbon costs are very dependent on what the bioenergy crop might be replacing. In the vehicle use phase also direct assessment of engine exhaust emissions is possible [5].

Table 2
Performance indicators of the biodiesel production system from rapeseed.

Indicator of performance	Value
Average feedstock yield	3.35 t/ha/yr
Average biodiesel yield	1200 L/ha
Total energy yield	44–102 GJ/ha/yr
Net energy yield	9–14 GJ/ha/yr
Output–input energy ratio	1.5–3.0
Energy content	32.6 MJ/L
Energy throughput	< 250 net MJ/h
Land requirement	< 0.100 ha/net GJ
Water requirement	3500–4500 m^3/ha/yr
Labour requirement	4 h/net GJ

Considering the whole life cycle, the advantages in terms of reduction of greenhouse effect and national fossil energy dependency are put into a clearer perspective. Biodiesel producers need to evaluate the environmental and energetical performances of their product in order to comply with sustainability criteria. As shown in Table 30, the EU default value for life cycle GHG emission savings for rape biodiesel complies with the legal minimum value (35%), at variance to soy biodiesel. Proper evaluation of a product should take into account many different social and environmental factors, in addition to energy yield, carbon budget and economic cost. Many studies have appeared that evaluate one or more of these aspects of biodiesel production, but only few make an attempt to present a more comprehensive evaluation [11,14,15,44–46]. Renewability is a useful measurement that can be used in conjunction with other measurements such as environmental and economic terms to assess biodiesel benefits.

4. Life cycle assessment of biodiesel

Life cycle assessment (LCA) according to the ISO standards 14040 (2006) and 14044 (2006) evaluates potential inputs (in terms of energy, environmental burdens) throughout the life cycle of a product, process or activity from the extraction of raw materials through production and use, to final disposal. The LCA approach is data intensive. There is a major international effort to improve the availability of data for LCA, but there is a general lack of local data in developing countries.

The rapid expansion in demand for biodiesel has raised concerns that feedstock production is causing both direct and indirect negative effects, such as water supply concerns, local environmental impacts on air, water and soil quality, habitat destruction and social issues (working conditions). LCA has become an important decision-making tool for promoting alternative fuels. Incorporating uncertainty in LCAs of biodiesel is essential to improve the reliability of such studies [47,48]. The shear amount of recent LCA studies (*cfr.* Table 4) indicates the importance attached to biodiesel.

The full LCA of biodiesel includes production of the raw materials and all their required inputs, utilisation of the raw and processed materials, and the disposal of materials. From a whole life-cycle viewpoint, a biodiesel pathway is a complex system (*cfr.* Fig. 2), which involves three economic sectors, namely agriculture, industry and services; covers all of the stages including raw materials cultivation/collection, fuel production, transportation to fuel storage and distribution; uses all sorts of

energy, including coal, petroleum products, natural gas, electricity, hydropower and other renewable energy, as well as fertilisers and agrochemicals.

The production of vegetable oils is commonly divided into three stages: agricultural stage, oil mill and refinery stage, and transport stage (from production to destination of use). The production of biodiesel again comprises these stages: pretreatment, transesterification and transport to the pump, ready for use by the consumer. The production and use of biodiesel entails emissions to the environment (air, water and soil) coming mainly from the use of fertilisers during the agricultural phase, emissions from fuel use and solvents during industrial operations (transportation, oil extraction, transesterification), and use (combustion). Several climatological factors (type of soil, weather) have a strong influence on environmental impact. Additionally, other significant factors are the past land-use, production or not of by-products, the technological process path and use of biodiesel either in a mixed or neat mode. Thus it makes sense to examine in detail LCAs of biodiesel from various (edible and non-edible) sources.

Limitations of the LCA method are several such as definition of system boundaries, allocation of impacts and temporal resolution. Table 3 also specifies differences in EU RED [7] and US EPA [49] GHG calculation methodologies. Most LCAs overlook soil carbon emissions from changes in land-use and hence they only provide a partial analysis in the sense that they only count the carbon benefits of using land for biodiesel crops and thus do not include other factors such as carbon costs, carbon storage and sequestration sacrificed by diverting land from its existing use [1]. Social sustainability is not considered by LCAs [50].

4.1. Life cycle boundaries

A most important stage in LCA is to set appropriate system boundaries (process stages considered, geographical coverage, timeframe, scale), and to define the reference systems used for comparison and the allocation of the environmental burdens among co-products. When the boundaries and other system assumptions are quite different a comparison between the results is often impractical and prone to misinterpretation.

The conventional diesel (CD) life cycle begins at crude oil extraction and ends at CD combustion. The vegetable oil (VO)-based biodiesel (BD) life cycle includes chemicals production and transportation, vegetable cultivation, harvesting and transportation, vegetable oil conversion and transportation, biodiesel conversion, storage and distribution and VO-based biodiesel oil combustion.

Life cycle assessment of biodiesel production requires a country or regional-specific approach (geographical reference area) due to the significant importance of local conditions. Regional specificities are a key factor when analysing the environmental impact of a biodiesel pathway through LCA. Due to different energy mixes (gas, petroleum, coal, *etc.*), transport distances, feedstocks (various seed oils), agricultural conditions (soil type; temperate or tropical; weather conditions), practices (*e.g.* tilling) and crop yields, as well as land-use (marginal and set-aside land) results can vary significantly from one country to another as well as in time (agricultural and technological advances). In particular, biodiesel LCAs are greatly affected by a nation's general energy mix, fertiliser production and utilisation and electricity generation and consumption. Clearly, the direct application of LCA studies for specific countries may not be extended automatically to other countries due to many differences, including agricultural practices, soil types, available technology, types and application rates of agrochemicals, distribution logistics of agricultural inputs and the country's energy profile. However, comparison of the energy consumption and GHG emissions of various biodiesel pathways in various conditions is useful to develop strategies and policies promoting large-scale development of the biodiesel industry at the most advanced level. LCAs are only valid for a given timeframe as technologies, production methods and prices are subject to change in the medium term. The effects of plant scale have been evaluated and range from small community [51] to large-scale biodiesel units [30,52]. Also the feasibility of large-scale production has been considered [11,14], *cfr.* also Section 6.3.

Table 3
Main differences between EU RED and US EPA GHG calculation methodologies for biodiesel.

Parameter	EU RED	US EPA
Base year	2008	2005
Reference value for diesel (g CO_2 eq/MJ)	83.8/90.3[a]	91.4
Allocation method	Net calorific value	System expansion/ economic value[b]
Indirect land-use change	Excluded	Included
GHG saving threshold (%)	35–60[c]	50–60[d]

[a] Most recent value.
[b] System-dependent allocation procedure.
[c] Current limit 35%, to increase to 50% in 2017, and 60% thereafter.
[d] The 50% for biodiesel from waste oil and 60% for cellulosic biodiesel.

4.2. Life cycle inventory allocation

In the course of biodiesel life cycles so-called coupled products are co-generated, such as rape straw, rapeseed oilcake and crude glycerol from the production of rapeseed methyl ester (RME). When comparing RME with the substitute fossil energy source, these additional products provide an additional usefulness, which must be accounted for. The method used to calculate co-product credits is a crucial issue in biodiesel life cycle assessments that should be addressed carefully. When dealing with multi-output processes as in case of biodiesel LCAs allocation is necessary. Allocation is defined as the partitioning or assignment of material inputs and environmental releases or outputs among the main product and co-products and wastes. Several approaches are being employed. These include a displacement method and more or less arbitrary allocations on the basis of mass- or volume-based partitioning, energy value, or economic revenue (market value).

In analysing farm-based processes economic, energy and weight allocations are the norm even though the "system boundary expansion" analysis method is preferred by ISO 14040:2006. In the substitution method, the system is expanded with avoided processes to remove additional functions related to the functional flows. The allocation approaches are less data-intensive and less challenging than the displacement approach. As stated in the ISO 14040-44 series, whenever more than one allocation method can be applied, a sensitivity analysis is required. The mass method, which allocates input energy to various co-products by their relative weights, provides reasonable results [53]. Various allocation approaches generate considerably different results [52,54]. Comparisons of LCAs based on different allocation modes are not recommended. Impacts are larger by switching from mass to energy content-based allocation [55]. Neither mass nor energy allocation is ideal for biodiesel systems because they do not recognise the nutritional difference between the oilseed meals. Since all of these meals are used almost exclusively for animal feed, valuing them on the basis of their mass or thermal energy contents is not the best approach. Physical allocation, based on well-defined inputs, invariable in time, is also recommended before economic allocation in ISO 14041. Allocation on price basis was applied in several rape diesel LCAs [30,56]. For rapeseed milling, the economic allocation factors are approximately 73% for

oil and 27% for meal; for FFB (fresh fruit bunch) and palm kernel milling, the allocation factors are 98% for oil and 2% for meal. Economic allocation factors vary with relative world market prices.

Allocation on the basis of energy inputs (as in [57]) is inappropriate as only biodiesel (and eventually straw) will actually be consumed in combustion for its energy content. The energy value-based allocation method is a favourable choice for a system in which the value of all the primary product and co-products can be determined on the basis of their energy content, such as the production processes of renewable fuels [7]. Moreover, allocation of the energy inputs to the by-products (*e.g.* [52,58–60]) may be the correct procedure on a small scale, where the by-products can replace other similar products, but does not necessarily apply on a very large scale. This already holds for the glycerol glut, but could equally well apply to meal in the future.

It is now generally accepted that the preferable method of determining co-product credits, which avoids allocation, is to perform a system expansion [61–63]. This is endorsed by ISO 14041. Weidema [62] used the method for determining the value of rapeseed meal in the biodiesel production process. The procedure has also been applied in the life cycle analysis of rapeseed oil in the agricultural stage [64], as well as for canola biodiesel [37,38] and soy biodiesel [38,65]. For allocation to crops in a cropping plan, *cfr.* Ref. [66].

4.3. Life cycle impact assessment (LCIA)

Life cycle results should always be presented relative to a baseline system, in this case petroleum diesel fuel. LCA assesses the additional quantity of energy required to turn the energy embodied in the raw materials into usable energy of the biodiesel. Direct energy consumption (petroleum products, electricity) and indirect energy consumption (used for production of materials and equipment) are evaluated in the fuel life cycle. The energy balance is defined as the energy consumed per unit of energy delivered. It includes the full life cycle energy consumption. There are two different energy balance measures that are important for biofuels, the total energy balance and the fossil energy balance. The biodiesel energy ratio (ratio of fuel energy to the total energy needed for biodiesel production) depends on climatic conditions and on the efficiency of the agro- and oil-processing technologies used. Rapeseed straw has a large impact on the energy ratio. Usage of rapeseed cake substantially improves energy conversion values, while the effect of glycerol is less. The impact of transportation and utilisation phase is a function of transport distance and the type of vehicle used. For renewability a positive energy balance ($EROI > 1$) is required. The continual adoption of new technologies in farming, oilcrop processing, and for biodiesel conversion affects the life cycle energy use over time, requiring update of LCA models.

The main question to be answered by LCA is whether biodiesel is environmentally friendlier than fossil diesel. There is an ongoing interest in the environmental assessment of biodiesel since early 1990 s [67]. Carbon emissions can by minimised throughout the life cycle of biodiesel production by application of sound science and engineering, agricultural best practice, maximising the use of biomass co-products (*i.e.* meal and glycerine) and by minimising transportation. In general, existing LCIA methods are associated with considerable uncertainties regarding toxicity. Most of the contributing emissions are pesticides (such as cypermethrin and chlorpyrifos) and heavy metals from fertilisers (meanly copper, zinc, chromium and nickel). Balances for the impact categories human toxicity and ecotoxicity are difficult to calculate because of insufficient databases in the area of fuel combustion.

The land-use metric (GJ/ha/yr) provides insight into the strategic use of land and is the most meaningful for the same land class. According to Weidema et al. [68], land-use covers a variety of aspects which must be included in life cycle assessment in different ways: area occupancy, land degradation and transformation, impact on biodiversity and aesthetic impact. Soil erosion caused by over-grazing is the greatest threat to agricultural land. Attention should be given to the land area used as well as to making an assessment of the quality and sustainability of land-use. Land-use is seldom being taken into account in today's LCAs since there are no impact assessment methods available. Mattson et al. [69] have formulated various impact sub-categories under the land-use category.

Blind spots in agricultural LCAs have been discussed by Schmidt [59]. Increased agricultural production can be met by increased yield or by increased area, *i.e.* transformation of non-productive land into agricultural land. This may include crop displacement. These two strategies carry significant differences in environmental impact: increased cultivated area has land-use effects, whilst increased yields may have more pronounced effects relating to global warming and eutrophication. The methodology to evaluate land-use change is still under development [70]. As land constraints and GHG emissions are a primary concern for EU27 emissions savings per unit area allow meaningful ranking.

Water is an important constraint on bioenergy production in many locations. The impacts of water use are usually not included in LCA by lack of data and agreed methodology for estimating the water footprint [71,72]. This is probably because LCA is largely a site-generic assessment tool, and incorporation of location and time specific data (*e.g.* for water use) is a considerable challenge [73]. The eco-scarcity method includes eco-factors for water use. There is currently no agreed methodology for estimating the impacts of biodiversity in LCA.

Standardisation of impact assessment methods is difficult [74]. Weighing methodology to aggregate LCA results in different environmental impact categories to one cumulative index has been described [75,76]. Different evaluation methods in LCIA use various policy criteria (Eco-scarcity, Eco-indicator 95, *etc.*) or monetary criteria (ExternE, EPS) and all focus on different impacts [77]. For example, the EPS method [78] concerns more resource depletion than emissions.

5. Life cycle assessments of Brassica biodiesels

Recent life cycle assessments of Brassica biodiesel pathways are reported in Table 4 and are discussed below according to the geographic area. Most rape biodiesel LCAs refer to winter oilseed crops, some have also considered spring oilseed rape [57,79]. Regular updates of LCAs are useful in the light of improved agricultural practices determining a rise in oilseed rape yield, different energy efficiency and emissions data for fertiliser production, and higher nitrous oxide emissions from the fertiliser manufacture process, *etc.* [80], as well as new industrial technologies. It follows that the most recent LCAs are best representing state-of-the-art. Also, LCA methodology and data are continuously being improved. In the future, more attention should be paid to the effects of land-use and allocations, particularly in scenarios of extended biodiesel mandates.

The reviewed LCAs differ in cultivation practices, extraction mode, business models (extraction annex biodiesel plant), trans-esterification strategy, production strategy (plant size), *etc.* LCA studies reported vary considerably from each other regarding assumptions made on agricultural yields, treatment of agricultural residues and allocation methods for high-value by-products. Both low and high rapeseed yield scenarios were reported

Table 4
Recent life cycle assessments of Brassica biodiesel pathways.

Feed	LCA framework	Functional unit	Application	Location	Tools	Methods	Impact categories	Year	Reference(s)
Rapeseed	WTW	100 km covered with a recent, middle size car	Combustion of biodiesel and diesel in passenger car	Greece	SimaPro 5.0	Eco-indicator 99	AP, AETP, CE, CED, EP, GWP, ORE, PM	2012	[81]
Rapeseed	WTW	1 MJ of combustion energy	Biodiesel production	China	–	–	EBR	2011	[19]
Rapeseed	WTP	1 MJ of combustion energy	Biodiesel production	Switzerland	–	CML, UBP 06	GWP, LUC	2011	[82]
Rapeseed, Soybean, Sunflower	WTP	1 kg of biodiesel produced	Biodiesel production	Unknown	–	Eco-indicator 99	EQ, HH, RD	2011	[83]
Rapeseed	WTW	One person-km driven by a regular bus	Combustion of biodiesel and diesel in diesel engines	China	SimaPro 7.0	IMPACT 2002+	CED, EQ, GWP, HH	2011	[84]
Canola	WTP	1 t of canola production	Biodiesel production from canola	Canada	GHGenius 3.19	–	GWP	2010	[37]
Rapeseed, Palm oil	WTP	1 t refined vegetable oil	Vegetable oil production	Europe (Denmark)	–	EDIP97, IMPACT 2002+, Eco-indicator 99	AP, BD, EP, ET, GWP, LU, ODP, PS	2010	[64]
Rapeseed, Sunflower	CTF	Production of 1 t of seeds per year	Oilseed production	Chile	Gabi 4.2	CML 2001, Eco-indicator 99	ADP, AP, EBR, EP, FAETP, GWP, HTP, LUC, MAETP, ODP, POCP, RAD, TETP, WF	2010	[85]
Canola, Tallow	WTW	1 kg of biodiesel produced	Biodiesel production	New Zealand	–	E4tech	GWP	2008	[36]
Rapeseed, Sunflower	WTW	3.2 Mt of biodiesel produced	Biodiesel production	Italy	–	–	EROI, GHG	2008	[11]
Rapeseed, Soybean	WTP	1 kg of biodiesel produced	Biodiesel production	Europe, Brazil	–	–	GHG, LUC	2008	[16]
Rapeseed	WTP	1 t of biodiesel produced	Biodiesel production	UK	–	EDIP 2003	GWP, TEC	2008	[30]
Rapeseed	WTP	1 kg of biodiesel produced	Biodiesel production	New Zealand	–	–	EB, GWP	2008	[86]
Rapeseed, Palm, Soybean, Used cooking oil, Bioethanol, Biogas	WTW	1 MJ of energy	Combustion	Switzerland	ecoinvent 1.3	Eco-Indicator 99, UBP 06	CED, GHG	2007	[87]
Rapeseed	WTP	1 t of biodiesel produced	Biodiesel production	–	SimaPro 6.0	CML 2000	ADP, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP	2007	[88]
Canola, Soybean	WTP	Biodiesel produced from 1.0 t of vegetable oil	Biodiesel production	Canada	–	–	EBR	2007	[38]
Rapeseed	WTW	1 kg of biodiesel produced	Biodiesel production	UK	–	–	EB, GHG	2006	[89]
Rapeseed, other vegetable oils	WTW	Unspecified	Biodiesel production	Europe	–	–	EB, GHG	2005	[90]
Rapeseed	WTP	Rapeseed from 1 ha/yr	Biodiesel production	Lithuania	–	–	EBR	2004	[59]
Rapeseed	WTP	1 MJ of combustion energy	Biodiesel production	Sweden	–	–	AP, EP, GWP, POCP	2004	[52]
B. carinata	WTW	Energy for 1 t grain	Biodiesel production	Italy	–	–	EBR	2003	[39]
Rapeseed	WTW	1 t biodiesel	Biodiesel production	UK	–	–	EROI, GHG	2003	[56]
Rapeseed	WTW	1 MJ of combustion energy	Combustion of biodiesel and diesel in diesel engines	Germany	–	–	AP, EB, EP, GWP, NP, ODP, POCP	2003	[34]
Rapeseed, Sunflower	WTP	1 MJ of biodiesel	Biodiesel production	France	–	–	EB, GHG	2002	[33]
Rapeseed, Soybean, Palm oil	CTF	1 ha oilcrop	Oilcrop production	Sweden, Brazil, Malaysia			LU	2000	[69]
Rapeseed	WTW	Rapeseed from 1 ha/yr	Biodiesel production	Germany	–	–	AP, EBR, GWP	1997	[91]
Rapeseed	WTW	Drive 100 km with an identical car in specified conditions	Comparison between biodiesel and diesel utilised to drive a car	Belgium, (W. Europe)	–	Nordic Manual, ExternE	AP, CED, EP, GWP, NRW, POCP, RW, WF	1996, 1998	[92,93]

CTF: Cradle-to-farm gate; WTP: Well-to-pump; WTW: Well-to-wheels. ADP: Abiotic depletion potential; AETP: Aquatic ecotoxicity potential; AP: Acidification potential; BD: Biodiversity; CE: Carcinogenic effects; CED: Non-renewable energy consumption; EB(R): Energy balance ratio; EP: Eutrophication potential; EQ: Ecosystem quality; EROI: Energy return on investment; ET: Ecotoxicity; FAETP: Fresh water aquatic ecotoxicity; GHG: Greenhouse gas; GWP: Global warming potential; HH: Human health; HTP: Human toxicity potential; LU: Land-use competition; LUC: Land-use change; MAETP: Marine aquatic ecotoxicity; NP: Nutrification potential; NRW: Non radioactive waste; ODP: Ozone layer depletion; ORE: Organic respiratory effects; PM: Particulate matter; POCP: Photochemical potential; PS: Photochemical smog; RAD: Radioactive radiation; RD: Resource depletion; RW: Radioactive waste; TEC: Total energy consumption; TETP: Terrestrial ecotoxicity potential; WF: Water footprint.

(*cfr.* Tables 13, 15, 22 and 25). Other issues evaluated considered local supply *vs.* global supply of vegetable oils, in particular to the EU (*cfr.* [64]), as well as imports of biodiesel.

Several co-products are generated in producing biodiesel from oilseed. Main co-products are straw (if removed from the field), protein meal (a by-product of oil extraction) and glycerine

(an industrial feedstock). Other main co-products are honey, beeswax, pollen, propolis and royal jelly (*cfr.* Fig. 2), and free fatty acids. The co-product potassium sulphate was explicitly considered by Ref. [36]; soapstocks have never been included in LCAs.

The most valuable agricultural co-product in the rape biodiesel life cycle is rapeseed meal, which can be used as animal fodder or alternatively for direct combustion or for generation of biogas [34]. Crop pressings also have potential value as biopesticides. Rapemeal may replace soymeal. Soybean meal dominates the protein meal sector for animal feed with about 67% of the total production; the next largest component is rapeseed or canola meal with 14%. Rapeseed contains 40% oil and 20% proteins. Heat-treating rapeseed meal (RSM) gives it the same feeding value as soymeal in milk production [94]. In terms of energy savings and GHG effect direct combustion of RSM is more favourable than fermentation to yield biogas or use as animal feed [34]. Large-scale feedstock production could lead to an excess of meal.

At variance to cereal straw, straw from rapeseed cultivation is seldom harvested as a fuel, but used in crop rotation to increase the humus content in the soil. In countries like Germany, Sweden, UK and Australia rapeseed straw is mostly incorporated into the soil. If crop residues produced from the agricultural phase are mostly left on field (as in the Canadian practice for canola and soybean cultivation) in order not to decrease the soil content of organic matter then straw is not a co-product. In some countries (*e.g.* Denmark) straw is utilised as a biofuel in vegetable oilcrop cultivation practices [64].

Free fatty acids are co-produced in the neutralisation process in the oil refining and subsequently esterified. Glycerine is generally a low-value co-product of vegetable oil transesterification, although some industrial processes enable production of refined glycerol for the pharma industry [95]. The proportion of bio-glycerine produced depends on the feedstock composition but is typically almost 10 wt% for refined vegetable oils. Large-scale biodiesel production creates a glycerine glut. Already, the co-product glycerine no longer finds a good market value and can be considered as an industrial waste. Efforts are being undertaken for its valorisation [96]. The energy used to produce biodiesel is to be allocated to biodiesel and its co-products.

5.1. Western European conditions

Eleven pre-2002 LCA approaches to the evaluation of energy and global warming aspects of biodiesel production from oilseed rape in the UK [57,79,80,97–100], Germany [101,102], Belgium [103] and Australia [104] were critically reviewed by Mortimer et al. [56]. These early studies report a wide range of energy requirements (0.33–0.89 MJ/MJ) and carbon requirements (from −0.091 to 0.036 kg CO_2/MJ). The main reason for the lowest (negative) carbon requirement of Ref. [57] is that all co-products (glycerine), by-products (rape meal) and waste products (straw), were assumed to be burnt as fuels, giving substantial energy and CO_2 emissions credits. Common factors exerting considerable influence over the final results are the nitrogen fertiliser input and consequent rapeseed yield, the energy and carbon requirements of nitrogen fertiliser, total energy inputs and CO_2 outputs of oilseed cultivation, reference systems for oilseed cultivation, oilseed processing data, and allocation procedures.

In European conditions considerable variations in nitrogen fertiliser inputs (83–290 kg N/ha/yr) and rapeseed yields (2200–4080 kg/ha/yr) were assumed to reflect typical agricultural practice, normally on a national scale. No general direct correlation between N fertiliser use and yield could be established. Identical rapeseed yields (3200 kg/ha/yr) were reported for N fertiliser input ranging from 185 kg N/ha/yr [79] to 290 kg N/ha/yr [97]. However, for winter oilseed rape cultivated in three different regimes (high intensity, nitrogen conserving, and mainly organic) with N fertiliser inputs of 180, 134 and 83 kg N/ha/yr, respectively, rapeseed yields were 3110, 2950 and 2540 kg/ha/yr, respectively [101]. The most efficient rate of N fertiliser application has been given as 180 kg N/ha/yr [98]. The primary energy consumption and CO_2 emissions from the manufacture of nitrogen fertiliser make significant contributions to the total energy inputs (4600–21,167 MJ/ha/yr) and CO_2 outputs (314–877 kg CO_2/ha/yr) of conventional rapeseed cultivation. The high total energy input of 21,167 MJ/ha/yr is a consequence of the high fertiliser energy requirement (59.70 MJ/kg N) [57]. The much lower total energy input of 13,254 MJ/ha/yr was observed for a high-yield cultivation where straw was ploughed in, determining a low fertiliser energy requirement (38.00 MJ/kg N) [98]. Also considerable differences were observed for the total energy input for the processing stage (drying, extraction, refining, transesterification), ranging from 9.60 MJ/kg RME [57] to 20.92 MJ/kg RME [79], *cfr.* Table 5. Extraction consists of either cold pressing and solvent treatment, or hot pressing and crushing. The energy required by crushing was grossly overestimated by Refs. [57,79] and has been reduced from 238 MJ/GJ to 12 MJ/GJ [97]. Methanol accounts considerably for the primary energy and CO_2 output of biodiesel. Process steps require careful optimisation.

Mortimer et al. [56] have evaluated the energy, global warming and socio-economic costs of producing rape biodiesel with typical 2002 UK values (Fig. 1). Assumptions were a rapeseed yield of 3.074 t/ha/yr, and an application rate for nitrogen fertiliser of 196 kg N/ha/yr. A crusher annex biodiesel plant was taken as the business model. Solvent extraction was applied with an extraction efficiency of 40.5%. The basis of allocation procedures was price. Table 6 shows the representative primary energy inputs and CO_2 and GHG outputs for the conventional process. In addition to CO_2 emissions, other GHG emissions, notably methane (1.032 kg CH_4/t BD) and N_2O (1.794 kg N_2O/t BD), can be released. N_2O emissions arise during the production of nitrogen fertiliser and, subsequently, as a result of its application to the soil during and after the cultivation of rapeseed. Total GHG output on account of the nitrogen fertiliser is 766 kg CO_2 eq/t BD, increasing the total GHG output for the conventional production of biodiesel from oilseed rape to 1516 (88) kg CO_2/t BD.

For a modified production process the following assumptions were made: (i) low-nitrogen cultivation method (81 kg N/ha/yr); (ii) rape straw utilisation to replace natural gas and fuel oil; and (iii) biodiesel utilisation instead of conventional diesel in agricultural machinery and for transportation. Tables 7 and 8 show that the primary energy input, CO_2 and GHG outputs are reduced by over 52%. The total primary energy input values per unit of energy in biodiesel from rapeseed in the UK (0.43(2) MJ/MJ for conventional production and 0.20(2) MJ/MJ for modified production) are at the lower extreme of the range of energy

Table 5
Biodiesel processing data.

Extraction method	Extraction	Methanol	Total processing	Reference
	Energy (MJ/kg RME)	Energy (MJ/kg MeOH)	Energy (MJ/kg RME)	
Crushing	3.47	19.70	9.60	[57]
Crushing	8.52	33.00	20.92	[79]
Solvent	2.78	38.09	11.43	[102]
Crushing	0.43	0	11.43	[98]

After Ref. [56].

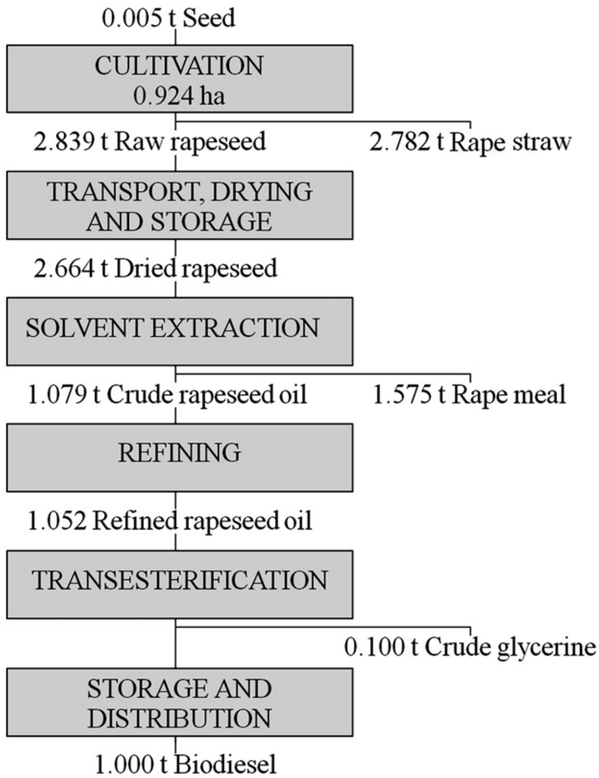

Fig. 1. Flowchart for the conventional production of biodiesel from rapeseed in the UK with solvent extraction. After Ref. [56].

Table 6
Representative primary energy inputs, CO_2 and GHG emissions for conventional production of biodiesel from rapeseed with solvent extraction in UK conditions.

Activity	Primary energy input (MJ/t BD)	Carbon dioxide output (kg CO_2/t BD)	Greenhouse gas output (kg CO_2 eq/t BD)
Cultivation			
Nitrogen fertiliser	3962 (556)	186 (27)	766 (75)
Other inputs less fallow set-aside	1845 (239)	93 (13)	96 (13)
Transport	511 (22)	33 (1)	33 (1)
Drying	566 (85)	41 (6)	41 (6)
Storage	214 (18)	17 (2)	18 (2)
Extraction	2394 (242)	113 (13)	120 (13)
Refining	411 (34)	26 (2)	27 (2)
Transesterification	5076 (607)	368 (40)	376 (40)
Plant construction and maintenance	162 (21)	7 (1)	7 (1)
Distribution	498 (21)	32 (1)	32 (1)
Totals	16,269 (896)	916 (52)	1516 (88)

After Ref. [56].

requirements from 0.33 to 0.89 MJ/MJ reported in the aforementioned earlier studies. Rowe et al. [21] cite an average value of 0.279 MJ/MJ for a systematic review of UK LCAs. The value of 0.011(1) kg CO_2/MJ using modified production is almost at midrange of the values of carbon requirements obtained in previous studies, which vary between −0.091 and 0.036 kg CO_2/MJ. The estimated values of the GHG requirement of biodiesel by conventional and modified production are 0.040(2) kg CO_2 eq/MJ (net) and 0.019(1) kg CO_2 eq/MJ (net), respectively. Rowe et al. [21] report a mean GHG output of 0.043 kg CO_2 eq/MJ.

The major three activities in terms of impact on energy and emissions are N fertiliser production and use, solvent extraction and transesterification. The effects of nitrogen fertiliser application rates and yield are linked. In particular, Table 9 shows that the single largest contribution to rape biodiesel production in terms of primary energy inputs and CO_2 emissions is associated with the transesterification process (especially as a result of methanol consumption), followed by manufacture and use of N fertiliser. The order is reversed for GHG emissions. Tailpipe emissions of CO_2 from vehicles using biodiesel are balanced by CO_2 absorbed during cultivation of the oilseed rape crop.

The assumed rapeseed yield, energy and GHG requirements of nitrogen fertiliser have a most pronounced influence on the results. A 15% reduction in yield to 2.6 t/ha/yr [105] produces a 6% increase in energy and carbon requirements of biodiesel; on the other hand, a yield increase to 4.08 t/ha/yr, or 33% above average UK value [98], reduces the energy and carbon requirements of biodiesel by about 15%.

As expected, the production of biodiesel uses less primary energy than that in the manufacture of conventional road transport fuels derived from fossil fuels. Table 8 shows that the total primary energy required for the conventional production of biodiesel from rapeseed is almost 63% lower than that needed for ultra-low sulphur diesel (ULSD). Even larger reductions, of about 83%, can be achieved by modified biodiesel production.

Biodiesel production from oilseed rape provided by a regional supply chain in North East England, based on local crops (4 t/ha/yr) supplying a seed processing facility, transesterification and finished blending facility (pipeline connected), was evaluated taking into account significantly different options for use of rape meal recovered during solvent extraction, namely as animal feed

Table 7
Representative energy inputs, CO_2 and GHG emissions for modified production of biodiesel from rapeseed with low-nitrogen cultivation, straw used as heating fuel and biodiesel replacing diesel fuel in agricultural machinery.

Activity	Primary energy input (MJ/t BD)	Carbon dioxide output (kg CO_2/t BD)	Greenhouse gas output (kg CO_2 eq/t BD)
Cultivation			
Nitrogen fertiliser	1739 (244)	82 (12)	336 (13)
Other inputs less fallow set-aside	243 (115)	−13 (6)	−11 (6)
Transport	140 (17)	8 (1)	8 (1)
Storage	227 (19)	11 (2)	12 (2)
Extraction	760 (58)	34 (5)	36 (15)
Refining	59 (6)	4 (1)	4 (1)
Transesterification	4274 (574)	296 (40)	302 (40)
Plant construction and maintenance	172 (22)	7 (1)	7 (1)
Distribution	136 (13)	8 (1)	8 (1)
Totals	7750 (638)	437 (42)	702 (53)

After Ref. [56].

Table 8
Energy, carbon and GHG requirements of different road transport fuels.

Fuel	Energy[a] (MJ/MJ)	Carbon[a] (kg CO_2/MJ)	GHG (kg CO_2 eq/MJ)
Rape biodiesel			
Conventional	0.43 (2)	0.024 (1)	0.040 (2)
Modified	0.20 (2)	0.011 (1)	0.019 (1)
Low sulphur diesel	1.13	0.078	0.085
Ultra-low sulphur diesel	1.17	0.081	0.088
Compressed natural gas	1.14	0.056	0.058

After Ref. [56].
[a] Per gross calorific value of the fuel.

Table 9
Relative contributions (%) to the primary energy input, CO_2 and GHG emissions from different activities for conventional and modified production of biodiesel from oilseed rape in the United Kingdom.

Activity	Primary energy input (MJ/t BD)		CO_2 output (kg CO_2 eq/t BD)		GHG output (kg CO_2 eq/t BD)	
	Conventional	Modified	Conventional	Modified	Conventional	Modified
Transesterification	35	55	40	67	25	43
N fertiliser	24	22	20	16[a,c]	51	47[a,c]
Solvent extraction	19	10	12	8	8	5
Cultivation	11[a]	3[a]	10[a]	–	6[a]	–
Others[b]	11	10	18	9	10	5

After Ref. [56].

[a] Corrected for credit.
[b] Refining, drying, storage, transport, construction and maintenance, distribution.
[c] Includes cultivation.

Table 10
Primary energy inputs and GHG emissions for production of biodiesel from oilseed rape in North East England with different options for rapemeal use.

Use of rapemeal	Energy requirement	Net savings of primary energy[a]		GHG emissions	Net GHG savings[a]	
	(MJ/t BD)	(MJ/MJ)	(%)	(kg CO_2 eq/t BD)	(kg CO_2 eq/MJ)	(%)
Animal feed	20,182 (978)	0.72	57	2004 (81)	0.033	38
Co-firing	1551 (1111)	1.22	97	1398 (103)	0.049	57

After Ref. [89].

[a] Relative to ULSD.

Table 11
LCA results for the production of rape biodiesel in the UK at both large and small scales.

Activity	Large scale		Small scale	
	Total energy (MJ/t BD)	GWP (kg CO_2 eq/t BD)	Total energy (MJ/t BD)	GWP (kg CO_2 eq/t BD)
Cultivation and harvesting	8389	1843	7508	1606
Transport of rapeseed	341	24	–	–
Drying	286	22	528	36
Storage	55	3	89	5
Oil extraction	2973	169	1512	87
Oil refining	923	53	–	–
Transport of oil	95	7	46	3
Transesterification	7177	270	10,226	446
Biodiesel storage	170	10	1	–
Transport to blending site	99	7	55	4
Transport to filling station	97	7	111	8
Total	20,605	2415	20,076	2195

After ref. [30].

(with price allocation) or for co-firing to generate electricity (with partitioning through substitution) [89]. Rape straw was regarded as waste. Table 10 shows the importance of the assumed use of rape meal as a by-product from biodiesel production. Co-firing of rape meal reduces considerably the estimated primary energy impacts and GHG emissions relative to its use as animal feed. Fertiliser application rates can be optimised to deliver yield benefits and, therefore, economic as well as environmental benefits. Maximum net primary energy savings per unit land area occur at a nitrogen fertiliser application rate of 184 kg N/ha/yr, maximum net CO_2 emissions savings at 230 kg N/ha/yr, and maximum total GHG emissions at 80 kg N/ha/yr. Comparison with the aforementioned conventional and modified production of rape biodiesel in the UK (Tables 6 and 7) is not straightforward given different assumptions regarding fertiliser application, N_2O emissions from soil, fossil energy consumption, recovery of rape straw, and allocations.

Stephenson et al. [30] have compared large-scale (> 100 kt/yr) and small-scale (< 10 kt/yr) rape biodiesel production in the UK in terms of total energy consumption (TEC) and global warming potential (GWP). In both cases, minimum tillage in cultivation was practised, as usual in the UK. For the large-scale production limestone ($CaCO_3$) was applied to most soils in order to maintain the appropriate pH. An average UK nitrogenous fertiliser rate of 211 kg N/ha was assumed, corresponding to 612 kg/ha ammonium nitrate. The average UK rapeseed yield was taken as 3.4 t/ha, where the seed contains 9 wt% moisture. Rape straw was ploughed back into the soil. For the small-scale biodiesel production only oilseed rape cultivated in East Anglia was used, where the agricultural procedure differs from usual UK practice because of highly fertile soils (chalky boulder clay). Nitrogenous fertiliser input was reduced to 160 kg N/ha and the average oilseed rape yield of 3.6 t/ha was 5.9% higher than UK average. The small-scale processing system differs from the large-scale in that drying, storage and crushing of the seeds occurred at the farm, rather than at a large-scale seed-crushing facility. Oil for large-scale production was extracted from the seeds by a separate solvent extraction/refining plant and transported to the biodiesel production plant by ship. Oil for small-scale production was extracted by cold pressing but not refined, and transported to the biodiesel production plant by road over 50 km. When biodiesel is produced on a large scale, the glycerine by-product is usually refined in an energy-intensive process and sold to the pharmaceutical industry. In small-scale plants, glycerine is usually treated as waste and sent to hazardous waste incinerators or sold on to refineries. Allocation of environmental burdens was based on market prices.

Although the total energy requirements for large- and small-scale production are similar, 20,605 and 20,016 MJ/t BD, respectively, there are important differences between stages (Table 11). Large-scale oil extraction and biodiesel production utilises significantly more water (2800 kg/t BD) than small-scale (600 kg/t BD). This is because small-scale extraction does not require water, but large-scale solvent extraction and refining requires water for the removal of phospholipids from the oil. Small-scale production of biodiesel in East Anglia saves 57% of energy input when compared to ULSD. Biodiesel produced on a large-scale saves

0.71 MJ/MJ of energy content, corresponding to 56% (*cfr.* 57% for large-scale biodiesel production in Ref. [89]).

Table 11 indicates that from the point of view of energy requirements, scale may have an influence, depending on whether or not small-scale producers are able to recover fully the unused methanol. If full methanol recovery is practicable, the scale of the process has limited impact on the energy requirement. Scale is not important for GWP as the impact from agriculture outweighs all other factors. Small-scale production of biodiesel in the UK emits 2195 kg CO_2 eq/t BD, saving 32% of GWP compared to ULSD. As shown in Table 11, GWP for small-scale production is about 10% lower than for large-scale production but significantly higher than reported in some other studies (1300 kg CO_2 eq/t BD [91] and 2004 kg CO_2 eq/t BD [89]), owing to a higher burden resulting from cultivation and harvesting. This arises from different assumptions regarding N_2O emissions from fallow set-aside soils and soils used to grow oilseed rape. Moreover, Mortimer et al. [89] omitted CO_2 emissions resulting from the application of limestone to acid soils. Biodiesel produced on a large-scale saves 0.022 kg CO_2 eq/MJ, corresponding to 26%, which is significantly lower than 38% reported by Mortimer et al. [89], again due to the aforementioned assumptions of higher field emissions. Transport involved in the various stages of manufacture (up to 260 km for large-scale plants) has little effect on GWP.

By changing the agricultural method used to produce oilseed rape from East Anglian practices to UK average procedures, the energy requirement and GWP increase to 23,300 MJ/t BD (16% increase) and 2700 kg CO_2 eq/t BD (22% increase), respectively. In that case, the large-scale production process has lower energy requirements (by 12%) and GWP (by 10%) than the small-scale production. By reducing the rate of application of N fertiliser from 211 to 100 kg/ha, use of cold pressing for extraction of oil from rapeseed, and combustion of rape meal and glycerine in a combined heat and power (CHP) plant, the total energy requirement would be reduced to almost −31,000 MJ/t BD and GWP to almost −750 kg CO_2 eq/t BD, corresponding to net energy and GWP savings from using biodiesel rather than ULSD of 170% and 120%, respectively.

Only 25–30% of the German biodiesel consumption comes from domestic feedstock; most of the imported feedstock comes from neighbouring countries. Left to market forces the German biodiesel production decreased from 2890 kt in 2007 to 2539 kt in 2009. Many LCA studies deal with various aspects of rape biodiesel in German conditions [34,35,67,90,91,101,102,106–108]. An early study [101] is mainly concerned with agricultural practices and the effect of the use of fertilisers on yield, primary energy input and emissions to the atmosphere for several biofuels including winter rapeseed. It was assumed that burning of oilseed rape straw would be commonplace so that this can be accounted as an energy credit. In a very thorough study Kaltschmitt et al. [102] have considered in particular the primary inputs of cultivation with a detailed derivation of the energy requirement for producing ammonia, calcium ammonium nitrate (CAN) and urea, resulting in a carbon requirement as low as 2.468 kg CO_2/kg N. Burning of rape meal results in the highest energy and emission savings. Various allocation procedures were evaluated. For cultivation a reference system of permanent or rotational fallow set-aside with occasional mowing was assumed. In Germany it is practically only possible to cultivate bioenergy crops on set-aside areas. Total primary energy input for biodiesel production amounted to 11.43 MJ/kg RME. Kaltschmitt et al. [91] have described RME production from winter rapeseed grown on rotational fallow, using allocation according to energy content of the coupled products. For the WTW life cycle RME shows a favourable energy balance as compared to fossil diesel (−30.9 GJ/ha/yr), favourable GWP (−2158 kg CO_2 eq/ha/yr), but unfavourable NO_X (+1582 g/ha/yr). The SO_2 balance reveals advantages compared with fossil fuel. Also the particulates are favourable. If we assume an additional utilisation of the rape straw for RME production, then the energy balance changes to even more favourable values.

More recently, Gärtner et al. [34] have refined the LCA of RME by considering more explicitly the impacts on LCA of the preceding crop effect, nitrous oxide emissions, production of honey and its co-products (beeswax, pollen, propolis and royal jelly) and rapeseed meal fermentation (Fig. 2).

- *Preceding crop effect*: In most LCAs of agricultural products fertilisation is particularly relevant. The value of the preceding crop comprises the soil improving properties of the crop (*e.g.* the fertilising effect of the residues remaining on the field, such as straw, roots and empty pods), serving as a nutrient source for the subsequent crop. This effect is particularly relevant for rapeseed plants. Crop rotation-specific nutrient conditions should be considered. An average preceding crop effect of 32.5 kg N/ha is often assumed for rapeseed [54]. Rapeseed positively affects the yield potential of subsequent crops.
- *Nitrous oxide emissions*: The release of nitrous oxide (N_2O) from soils is caused by microbial activity. The emission depends on various factors. By taking into account N_2O emissions from rotational set-aside land (on the basis of 50% of the fertiliser-induced emissions according to IPCC) the GHG savings by RME are higher than previously assumed in most LCAs, while the additional nitrous oxide emission turns out to be smaller.
- *Production of honey and co-products*: Honey and its co-products only marginally affect the LCA results of RME.
- *Biogas generation from rapeseed meal*: Instead of using rapeseed meal as animal feed (which is currently the most common use), it can also be fermented in a biogas plant and subsequently used in energy generation. In terms of energy savings and GHG effect direct combustion of rapeseed meal is more favourable than fermentation to yield biogas, which in turn is more favourable than the use of rapeseed meal as animal feed. Environmental advantages are recorded for greenhouse effect, disadvantages for acidification and nutrient impacts. With regard to ozone depletion biogas generation has an additional advantage in comparison with the animal feed option. The potential fermentation of rapeseed meal markedly extends the life cycle of RME. Supplementary consideration of the production of honey and its co-products from the rapeseed fields as well as the preceding crop effect of rapeseed do not entail significant changes to the LCA results.

An LCA inventory of rape biodiesel, as shown in Table 12 for energy expenditures, CO_2 eq and NO_X emissions, shows that RME has significantly better energy efficiency and less CO_2 output than conventional diesel fuel; however, the latter has a better NO_X balance [90]. The preservation of fossil energy sources and the greenhouse effect have the greatest political significance in Europa. RME causes more emissions in the impact categories of acidification and eutrophication compared with conventional diesel fuel, whereas no clear result is obtained concerning smog, ozone depletion and human- and eco-toxcity.

Rathke et al. [35] have determined the energy balance of winter oilseed rape (OSR) cropping as related to nitrogen supply (CAN or cattle manure slurry, from 0 to 240 kg N/ha/yr) and preceding crop considering two crop rotation systems, namely winter barley-winter OSR-winter wheat and pea-winter OSR-winter wheat. Not unexpectedly, different N management strategies strongly influence the energy balance of winter oilseed rape. Under identical site conditions, the input of energy to winter OSR was highly variable ranging from 7.42 GJ/ha (for unfertilised OSR following winter barley) to 16.1 GJ/ha (for 240 kg N/ha organic fertilisation of OSR following winter barley). The lowest energy output (174 GJ/ha), *i.e.* energy from seed and straw of

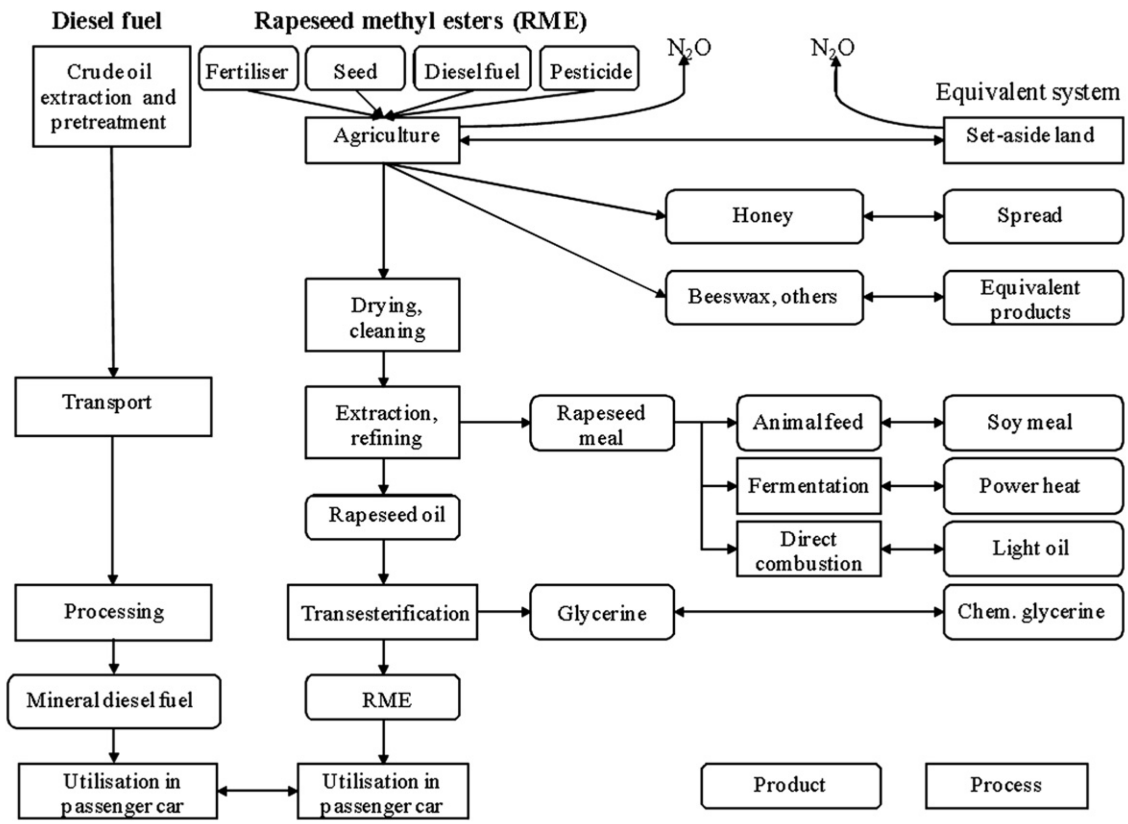

Fig. 2. Life cycles 'from cradle-to-grave' for fossil diesel fuel and rape biodiesel (RME). After Ref. [34].

Table 12
Energetic expenditures (finite energy) and selected emissions (CO_2 eq, NO_X) for biodiesel from rapeseed and diesel fuel.[a]

Activity	Calculated final energy demand (MJ/kg)	CO_2 eq (g/kg)	NO_X (g/kg)
Rape biodiesel			
Cultivation	11.36	2043	4474
Industrial	13.49	893	1219
Energetic use	0.22	233	10,348
Credits RME	−31.61	−1971	−4998
Diesel fuel			
Industrial	4.82	374	649
Use	42.96	3392	10,190
RME minus diesel fuel	−54.32	−2569	204

After Ref. [90].

[a] All values refer to 1 kg diesel fuel, *i.e.* 1 kg diesel fuel eq of RME.

Table 13
Energy balance and greenhouse gas emissions for French rapeseed.

Product	Yield (t/ha)	Energy input (MJ/kg)	EROI	GHG emissions (g CO_2 eq/MJ)
RSO	3.34	7.95	4.7	17.8
RME[a]		12.5	3.0	20.2[b]/23.7[c]
RSO	3.64	7.30	5.1	16.2
RME		11.30[d]	3.3[d]/ 2.8[e]	17.6[b,d]/21.0[b,e]

After Ref. [33].

[a] Homogeneous transesterification.
[b] Before combustion.
[c] After combustion.
[d] Biodiesel purification by washing.
[e] Heterogeneous transesterification.

winter OSR, resulted when OSR receiving 80 kg N/ha as organic fertilisers followed winter barley. The energy output increased to 262 GJ/ha for winter OSR receiving 240 kg N/ha as mineral fertiliser followed pea. Under the given conditions, the positive effects of the previous crop pea and mineral N fertiliser could not be compensated by winter barley as a previous crop and organic fertiliser. The most favourable N rate for maximising energy gain or net energy output (250 GJ/ha) was 240 kg N/ha, while that needed for minimum energy intensity (energy input per unit grain equivalent GE) of 91.3 MJ/GE was 80 kg N/ha, and for maximising output/input ratio (29.8) was 0 kg N/ha.

French rapeseed is grown all over the country (except in the South) in rotation with wheat in conditions of non-irrigation. Using 170 kg N/ha (AN, ammonium sulphate) and pesticides (3.7 kg a.i./ha) a yield of 3.34 t/ha is obtained (2002), up to 3.64 t/ha by 2009 (forecast). Oil content is 46% (on dry weight basis). The results of an LCA with system expansion for the agricultural stage (straw not considered) and mass allocation for the industrial stage are summarised in Table 13. The fossil energy input for RSO is 19.0 GJ/ha or 7.95 MJ/kg (78% cultivation, 15% pressing); the energy balance is 4.7 MJ/MJ [33]. GHG emissions for RSO amount to 600 g CO_2 eq/kg RSO or 17.8 g CO_2 eq/MJ RSO. The fossil energy input for RME (homogeneous transesterification) is 12.5 MJ/kg with the following contributions: agriculture 45%; oil pressing 8%; refining 2%; methanol production 26%; transesterification 16%; storage/transport/distribution 3%. The energy balance of homogeneous RME is 3.0 MJ/MJ. GHG emissions for RME amount to 755 g CO_2 eq/kg RME or 20.2 g CO_2 eq/MJ RME. Improvement in the industrial stage (transesterification) may be achieved by energy demanding ester purification by distillation, low energy-demanding ester purification by washing (yields low glycerine quality) or by heterogeneous catalytic transesterification (high energy-demanding process; yields high-purity

glycerol) [95]; *cfr*. also Section 7. The effects on energy balance and GHG emissions of some of these technological improvements are indicated in Table 13. Heterogeneous transesterification (IFP) leads to a decrease in energy performance of the transesterification stage of 72% and a decrease in EROI to 2.8 MJ/MJ.

Also in Belgian (Western European) conditions the ecobalance of winter rapeseed biodiesel indicates that the agricultural part of the life cycle contributes more than 50% to most impact categories. Production and transportation of fertilisers heavily determine the contribution to this agricultural part. Crop growing and field work primarily contribute to the energy-related impact categories acidification (35%) and eutrophication (65%). As to the industrial part of the biodiesel chain, the transesterification process is a dominant contributor to the impact categories fossil fuel requirement (CED), water footprint (WF) and photochemical oxidants (POCP, $>60\%$). Extraction of the oil has much less impact. Use of biodiesel in a conventional diesel engine is the primary contribution to the energy-related impact categories and contributes more than 40% to acidification caused by NO_X emission during combustion. Fig. 3 compares the environmental profiles of rape biodiesel and petrodiesel. The biodiesel life-cycle has a better effect score only for the use of fossil fuels and the greenhouse effect. The better ecobalance for the GHG effect is partly due to the fact that rapeseed assimilates CO_2 during plant growth. Fig. 3 also shows that biodiesel consumes more water and produces more waste during its life cycle [93].

The environmental profiles – which do not have a common denominator – can be expressed as one environmental index via normalisation using eco-indicators. It then appears that fossil diesel is favoured over rape biodiesel in Belgium [92]. However, calculating environmental indexes requires the use of weighing factors which represent the relative seriousness of the impact category considered. These are highly subjective, can differ largely from country to country, and are subject to political views.

De Nocker et al. [93] have also applied an external cost methodology based on the ExternE (Externalities of Energy) approach [109] for comparison of rape biodiesel and petrodiesel. This analysis estimates the damages to public health, materials, agriculture and global warming (social costs). The external cost analysis indicates the importance of emissions of particles in the use phase of both fuels, as well as the public health impact from NO_X (via nitrates). External cost analysis shows that site and technology specificity needs to be taken into account, as the damages from particle emissions in the use phase (diesel transport) are much higher compared to emissions in other stages. The impacts of emissions of particles, which originate for 90% from use, depend very much on the population density near roads. For global warming site specificity is obviously not an issue. External costs are high for both biodiesel and fossil diesel but more favourable (5–20%) for the former [93]. However, in terms of total costs (production costs+external environmental damage cost) fossil diesel scores better.

LCA and external cost methodology are complementary and lead to different insights. LCA identifies *potential* impacts, whereas the external cost analysis aims at quantifying *real* impacts. It is useful to use both methods. Application of both approaches indicates that although biodiesel offers advantages in terms of GHG emissions, it has similar or higher impacts on public health and the environment. As our appreciation and scientific understanding of the impact changes, these methodologies require regular updating. Another problem is the fact that not all emissions can be attributed to a specific country or even continent.

Switzerland faces the choice between use of scarce arable land for food production and import of fuels or production of fuels from oilcrops and import of displaced food. Reinhard et al. [82] have used consequential LCA (CLCA) to quantify the direct and indirect environmental impacts of increased domestic production of RME (for substitution of 1% of the annual Swiss diesel consumption) by replacing edible rape oil, assuming that the displaced product is compensated for by increasing imports of a functionally equivalent product, *i.e.* European rape or sunflower oil or palm oil from Malaysia (replacement by soy oil from Brazil was not evaluated). The increased use of rape oil for RME production in Switzerland thus causes an additional production of vegetable oils on the world market. This has a negative influence on many environmental impact factors. Increased production of vegetable oils elsewhere causes also an indirect availability of meal on the global market.

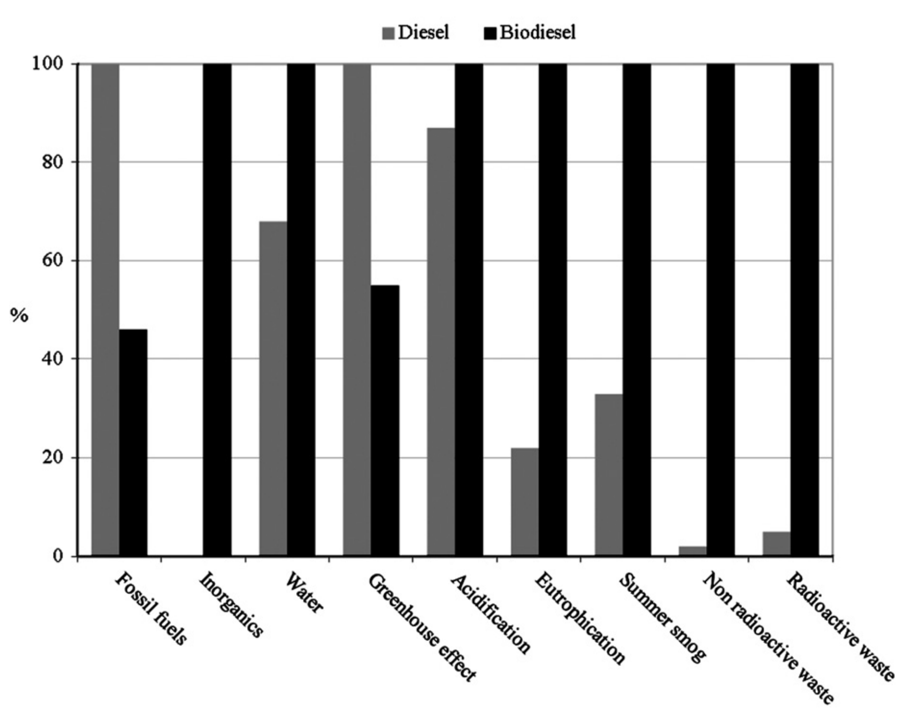

Fig. 3. Comparison of the environmental profiles of winter rape biodiesel and diesel. After Ref. [93].

Displacing food production by RME production in Switzerland can locally reduce total GHG emissions when GHG-intense soy meal from Brazil is substituted by rape and sunflower meal, which is a co-product of the vegetable oil production [82]. Additional domestic production of RME also leads to an increase in glycerine. In total, RME production in Switzerland is attributed with the environmental burdens inherent to the additional production of palm oil and credited with burdens stemming from avoided soybean meal production. The environmental burdens were compared by means of CML indicators, land-use and the Swiss method of ecological scarcity (Environmental Impact Points, UBP 06) [110,111], which reflects the total effects to the environment.

As regards rape and sunflower oil, the main impacts stem from the agricultural production itself. With regard to palm oil, the CO_2 emissions from land-use change (LUC) dominate the results, in particular the devastation of rain forest on peat land. The additional production of palm oil in Malaysia causes the highest emissions (345 g CO_2 eq/MJ) primarily due to the considered LUCs which cause about 90% of the emissions. If these emissions can be avoided, as for plantations grown on marginal land, the net impacts related to palm oil production decrease significantly. The net GHG emissions of palm oil imports to Switzerland are significantly higher than for rape or sunflower oil (329 compared to 58 and 74 g CO_2 eq, respectively). The results of other environmental indicators show a mixed pattern (Table 14). In general, the highest impacts for most categories are caused by substitution by import of rape (R) oil. Anyway, all three oil impact scenarios of Table 14 lead to higher total environmental impacts than the production and use of fossil fuels.

Alternatively, increased RME production in Switzerland can also be met by displacement of feed barley. Less Swiss barley and straw is to be compensated by import of these commodities either from Europe (by agricultural intensification or expansion) or from Canada (area expansion). Only increased agricultural production by intensification leads to lower GHG emissions *and* lower overall environmental impacts than the fossil reference. High-yield agriculture shows global warming [112]. The paper by Reinhard et al. [82] shows the strong interdependence of global replacement options. The impacts of an increased RME production in Switzerland depend more on the environmental scores of the replacement products on a global scale than on local production factors. Given the constraints on European agriculture characterised by an overall slightly decreasing area [113] and a diminishing rate of increase in yield [114] long-term options for crops/oil are most likely to be extra-European (with greater GWP and total environmental impact). Therefore, it seems best to focus production of biodiesel on feedstocks that are decoupled from the global food and feed markets, such as use of non-edible energy crops that grow specifically on degraded land. This conforms to the conclusion expressed in the Gallagher Review [8].

A recent energy comparison for rape, sunflower and soybean in European agricultural systems has shown considerable margin for improvement in many areas with low yields. The main output data for rapeseed and rape oil (mainly from North-Central Europe) denote a wide regional variability (Table 15). Also crop input data (Table 16) show considerable variability. Table 17 shows a breakdown of field inputs, where the most relevant contributions are fuel and nitrogen (fertilisers). Fuel use is particularly high in sloping areas or in difficult soil conditions. Table 18 shows that the energy balance (both in terms of net gain and ratio) is always favourable for rapeseed. However, the balance gets worse for its methyl esters (Table 19), both with and without allocation for co-products. Crop input can be diminished by reduction or by rationalisation of technical tools. Use of high capacity machines, which achieve considerable reduction of time per unit area, may reduce crop input while maintaining high yields. Although energy gains are possible by technical rationalisation, this does not guarantee a positive economic result. In fact, it is necessary to strike a balance between energy and economic aspects by operating in such a way that output is significantly higher than 15–20 GJ/ha for rapeseed, while finding technical means to reduce input costs without significantly affecting yield.

Table 14
Impact assessment of low-sulphur diesel, attributional RME and RME at the expense of available rape oil.[a]

Impact indicator	Unit	Diesel	RME	RME-R	RME-S	RME-P
Abiotic depletion (SB eq)	mg MJ^{-1}	566	235	295	189	115
Acidification (SO_2 eq)	mg MJ^{-1}	226	488	483	227	272
Eutrophication (PO_4 eq)	mg MJ^{-1}	41	361	272	1119	167
GWP (100 CO_2 eq)	g MJ^{-1}	89	62	58	74	329
Ozone depletion (CFC-11 eq)	mg MJ^{-1}	1.3E−02	3.5E−0.3	−6.6E−0.3	−7.8E−0.3	−9.5E−0.3
Human toxicity (1.4-DCB eq)	g MJ^{-1}	9	19	40	17	14
Terrestrial ecotoxicity (1.4-DCB eq)	mg MJ^{-1}	84	46,645	184,851	11,953	46,103
Photochemical oxidation (C_2H_4 eq)	mg MJ^{-1}	14	5	11	10	45
Land-use	dm^2 MJ^{-1}	0.0035	17	5	48	6
EP[b]	–	88	214	307	410	192

After Ref. [82].

[a] Substituted by import rape (R) oil, sunflower (S) oil and palm (P) oil.
[b] Environmental Impact Point (Swiss ecological scarcity method [110]).

Table 15
Rapeseed: seed, oil and energy production.

Grains Yield range (t/ha)[a]	Oil[a]		Specific energy[b]		Energy output range		
	Content range (%)	Yield range (t/ha)	Grain (MJ/kg)	Oil (MJ/kg)	Grain (GJ/ha)	Oil (GJ/ha)	Meal (GJ/ha)
0.7–3.4	35–40	0.3–1.4	24.0	37.4	16.8–81.6	11.2–52.3	5.6–29.3

After Ref. [60].

[a] Min. and max. values for European countries (FAO data, average 5 years 1996–2000).
[b] Average data.

Table 16
Field phase inputs for rapeseed cultivation.

Fuel		Fertilisers		Pesticides		Others[b]		Total
(GJ/ha)	(%)	(GJ/ha)	(%)	(GJ/ha)	(%)	(GJ/ha)	(%)	(GJ/ha)
5.0–19.0[a]	38.5–51.4	5.6–11.9	43.1–32.2	0.2–0.9	1.5–2.4	2.2–5.2	16.9–14.0	13–37

After Ref. [60].
[a] Hilly areas.
[b] Seeds, machineries.

Table 17
Energy requirements for field phase of rapeseed cultivation.

Field action	Energy requirements (GJ/ha)
Tillage	3.5–14.4
Sowing	0.5–1.4
Fertilisation	5.6–13.8
Weed and pest control	0.8–1.9
Harvesting	2.6–5.5
Total	13.0–37.0

After Ref. [60].

Table 18
Rapeseed: inputs and energy balance for production phase.

Production phase input range (GJ/ha)	Energy balance range	
	Ratio output–input	Gain output–input (GJ/ha)
13–37	1.38–2.21	3.8–44.6

After Ref. [60].

Table 19
Rapeseed methyl ester: oil energy balance range.

Ratio output–input		Gain output–input (GJ/ha)	
Without allocation	With allocation	Without allocation	With allocation
0.7–1.0	1.0–1.5	−4.7–1.0	0.4–24.0

After Ref. [60].

5.2. Nordic conditions

Bernesson et al. [52] have focused on the industrial scale effect of RME biodiesel plants in Central Sweden. Scales considered (in terms of area serviced, nameplate capacity and transport distances) were as follows: small (40 ha, 44 t/yr, nihil), medium (1 kha, 1.1 kt/yr, 7 km) and large (55 kt/yr, 50 kha, 110 km). Small-scale systems are of interest because of simple and less expensive process technologies and benefits to rural employment. Large-scale systems allow more economical operation. Small-scale production minimises transport of rapeseed to the production plant and of products (RME and meal) to the consumer. In small-scale plants rapeseed oil is extracted mechanically. In large plants, extraction takes place in two steps, pressing and hexane extraction, resulting in higher oil yields. The higher extraction efficiency and use of machinery and infrastructure in the large-scale systems is outweighed by the longer transport distances. For the medium-scale system, the same operations were used as for the large scale, except for hexane extraction. Cultivation, production of methanol and catalyst (KOH) were identical for all scales.

Table 20
Comparison of different allocation methods for three RME production scales in Swedish conditions.

Allocation	GWP (g CO_2 eq/MJ fuel)	AP (mg SO_2 eq/MJ fuel)	Input energy (kJ/MJ fuel)
None	87.6/79.5/61.9[a]	519/471/366	569/497/407
Physical[b]	40.3/39.5/40.2	236/232/236	295/277/284
Economic	51.1/49.1/45.8	301/289/270	355/327/313
Expanded	34.5/32.1/30.9	19/46/161	−367/−342/−147

After Ref. [52].
[a] Small-/medium-/large-scale.
[b] Physical allocation after energy content.

The total energy required for cultivation of winter rapeseed and the environmental outputs were 11.8 GJ/ha and 2405 kg CO_2 eq/ha, with a total energy content of rapeseed of 63.9 GJ/ha; the energy ratio is 5.4. The energy requirements for the various RME production stages were as follows: agricultural production, 65%; methanol production, 12%; extraction, 10%; transesterification, 11%; embodied energy (machines, buildings), 1.4%. For large-scale plants, the energy requirement for transport (in absolute terms) increases by a factor of almost 20 in comparison to small-scale plants. In relative terms the change is rather small in relation to the total energy requirement of the production system. All process energy was assumed to be electricity. Average Swedish energy production is based on hydropower (48%), nuclear power (44%), fossil fuels (4%) and biofuels (3%).

For comparison of different biodiesels and production strategies it is crucial to refer to results obtained with the same allocations and system limitations. Energy requirements and environmental burdens are greatly dependent on the allocation between RME and co-products (meal, glycerine), as shown in Table 20. Without allocation, all energy used and emissions are solely burdened by RME. For small plants and physical allocation, GWP was 40.3 g CO_2 eq/MJ fuel and the energy requirement 295 kJ/MJ fuel. In the expanded allocation mode rapeseed produced in the large-scale plant could replace (overseas) soymeal, and so that the rapemeal with high oil content produced in the medium- and small-scale plants could replace soymeal mixed with soyoil. Negative values for the energy requirement indicate that the system was a net supplier of energy. This was possible because the energy subtracted for replaced by-products (in the expanded allocation mode) exceeded the total energy needed for production of RME. The results are similar to those by Gärtner et al. [106,107] for small-scale RME production in German conditions using expanded system allocation.

Differences in environmental impacts (GWP, AP, EP, POCP) and energy requirement between the systems were small to negligible, not unlike findings for different production scales in UK conditions (economic allocation mode) [30]. The dominating production step regarding environmental impact and energy requirements is cultivation and this step is identical for all production scales. For the small-scale system the environmental

impact from rapeseed production accounted for 95% of the total impact for all emission categories. Production of methanol was responsible for 0.7–2.5% of the environmental impacts, whereas electricity was responsible for a few percent. At equal environmental load, larger plants are to be preferred as production costs are reduced by 36% and 50% for medium- to large-scale production, respectively.

To decrease the environmental impact of RME production, several options are available. Increased seed harvest (constrained by biological factors and weather conditions) and decreased use of synthetic fertilisers decrease the impact considerably. Organic waste and sewage water can be used to fulfil the nutrient demands with a very limited energy cost, thereby also avoiding high costs for cleaning plants. Waste products normally not allowed in agriculture can be used for non-food rapeseed. However, organic waste and sewage water may contain heavy metals, pesticide residues and other undesired organic substances.

Production and use of RME reduce GWP and POCP in comparison to diesel oil (MK1), namely from 217 to 127 g CO_2 eq/MJ_{engine}, and from 68 to 23 mg C_2H_4 eq/MJ_{engine}, respectively. However, the categories of AP and EP increase by 79% and 81%, respectively, in comparison to MK1. The energy requirement for the production and use of RME was 4.8 times higher than for MK1.

Schmidt [64] has presented a comparative LCA of the environmental impacts associated with the local *vs.* global supply of vegetable oil (Danish rapeseed as a good representative of EU rapeseed, and palm oil from the IndoMalay region) to the European market. Palm oil and rapeseed oil are substitutable products for most food purposes. It has been assumed that 40% of the increase in Danish rapeseed production is met by local increased yields, and 60% by increased area which displaces spring barley, as in Switzerland [82]. Using the consequential approach to system delimitation (CLCA) [115], co-product allocation was avoided by the system expansion. It is not possible to give a straight answer as to which oil is the environmentally preferable. It depends on how increased production is achieved (area or yield), and on uncertainties related to transportation impacts. The impacts on biodiversity are uncertain and very sensitive to the boundary settings and assumptions on ecosystem vulnerability in the LCIA method. For equal ecosystem vulnerability for all regions, rapeseed oil would have a smaller impact on biodiversity than palm oil [64]. Palm oil is environmentally preferable to rapeseed oil for the impact categories ozone depletion (ODP), acidification (AP), eutrophication (EP), photochemical smog (PS), and land-use (LU), whilst the differences for global warming (GWP), biodiversity (BD) and ecotoxicity (ET) are less clear. The difference in the contribution to global warming from rapeseed and palm oil is limited if increased production is achieved by a change in cultivated area and if increased rapeseed cultivation is achieved locally. The most significant process contributing to global warming from RSO is rapeseed cultivation. The use of straw as a biofuel in Danish vegetable oilcrop cultivation practices leads to a higher contribution to global warming. For global warming, palm oil is preferable to rapeseed oil if increased productivity is achieved by increased yield. Significantly higher contributions to global warming can be expected in higher rapeseed yield scenarios. This is due to the fact that the level of fertiliser application is already very high, and therefore, the crop response to additional fertiliser is relatively low. Moreover, use of fertilisers in the EU is regulated by maximum N norms [41,42,116]. Instead of additional application of fertiliser, another way of increasing yields in the EU is through biotechnology (but highly controversial in many EU countries). Local expansions of cultivated area on set-aside area are preferable to displacement of crops which are compensated for by increased agricultural production abroad. This only allows small increases in production in most European countries. Full press technology in the oil mill is preferable to solvent extraction.

At the 2004 levels of rapeseed productivity in Lithuania (1.8 t/ha), and without implementing energy-saving technologies in agricultural and industrial processing, the energy obtained from RME is almost equal to that used for its production. The energy ratio (biodiesel fuel energy *vs.* total energy used for production) of 1.04 is substantially lower than the EU average energy ratio of 1.9 [117] despite the fact that the Lithuanian energy mix is rather favourable (including 80–85% nuclear energy and 2.5% hydro-energy). Energy accumulated in fertilisers makes up more than 58% of the total energy consumption in agriculture in Lithuania [59]. Using biofertilisers and advanced seed preservation technology reduces the total energy consumption of 18,591 MJ/ha with as much as 8937 MJ/ha or 48%. Upon the implementation of several agro-technological innovations (usage of biofertilisers, improved seed preservation) with a rapeseed productivity of 3 t/ha and energy-saving biodiesel fuel production methods (biotechnological oil extraction and high-productivity transesterification) the energy ratio for REE would be higher than for RME and exceed European average (RME based) [59]. The resulting better energetic performance of REE as compared to RME is somewhat surprising if one considers the considerably higher energy consumption of ethanolysis (*cfr.* Table 26). Nevertheless, this work shows the potential opportunities to improve the life cycle energy efficiency, in particular as to the agricultural stage. Ethanolysis was also evaluated by Harding et al. [88], *cfr.* Section 5.7.

5.3. Southern European conditions

Also Italy – like many other European countries – faces the issue of using scarce arable land for food production and importing biodiesel or to produce biodiesel from domestic vegetable oilcrops and import food. Russi has questioned the desirability of large-scale consumption of biodiesel in Italy (or 3.2 Mt/yr, being the 5.75% by energy transport target 2010 according to European Directive 2003/30/EC), taking into account social, environmental and economic factors [11]. The Italian biodiesel production (2009) amounted to only 737 kt/yr (from 80% RSO, 20% SNO; partly imported) with an oversized nameplate capacity (2010) of 2375 kt/yr. Table 21 shows severe impacts of large-scale biodiesel

Table 21
Social and environmental impacts of large-scale biodiesel production in Italy.

Domestic production	
+	Local rural development
+	Modest energy savings (locally)
+	Minor reduction in GHG emissions
+	Reduced urban pollution
−	Oilseed production from earmarked crops
−	Replacement of cereals and fodder plants
−	Land requirement (corrected for avoided land-use)
−	High production costs (intensive agriculture)
−	Eutrophication (fertilisers)
−	Huge increase in food imports
−	Decrease in fiscal energy revenues
Biodiesel import	
+	No competition with food production
+	No domestic land requirement
+	Reduction in energy dependency
+	Major reduction in GHG emissions
+	Reduced urban pollution
−	Environmental impacts (elsewhere)
−	No benefit to domestic rural sector
−	Decrease in fiscal energy revenues

+, Advantage. −, Disadvantage.

consumption in Italy, both in case of domestic production and for imports (of RSO from E. European abandoned land). For a 3.2 Mt biodiesel requirement approximately 3.7 Mha land is needed, which can simply not be made available in this densely populated country (191 pp/km^2) with much uneven agricultural land; Italian set-aside land amounted to only 0.3 Mha in 2005. The reduction in energy dependency would only be about 2%. As a result, a plea was made for an alternative strategy, namely supporting organic agriculture for food production instead of subsidising biodiesel. This could also help counteracting the present severe soil erosion of many abandoned Italian agricultural areas. However, there is still the necessity to solve Italy's present and future needs for liquid fuels. While domestic energy farming in Italy can only make limited contributions to biofuel manufacture, in the long term the countries' chronical addiction to fossil fuels is no longer sustainable. Specifically, at short term Italy is best served by a less wasteful attitude of its citizens (energy saving), in the medium to long term by investing public resources in a more renewable and less expensive energy mix.

Several studies have demonstrated the feasibility of using Ethiopian mustard (*B. carinata*) oil for producing biodiesel [39,118,119]. The *B. carinata* system cultivated in Southern Europe is energetically efficient. Gasol et al. [120] have evaluated the energy balance and environmental impacts of this crop in Spain. The total primary energy consumption of the *B. carinata* cropping system has been estimated at 10.26 GJ/ha, with 76% on account of the agricultural production and 24% for the transport phase [120]. Studies of this same crop in Italy have reported values between 9.91 and 19.27 GJ/ha depending on the intensity of the cultivation [39]. This difference is mainly on account of a 32% lower fertiliser dose in Spanish agricultural conditions. The contribution of the *B. carinata* cropping system to the global warming is 12.7 g CO_2 eq./MJ biomass produced. In Spanish conditions, the use of fertilisers represents 51% to 68% of the impact in six of the ten environmental categories considered (GWP, FAETP, MAETP, TETP, AP, EP), whereas the second most important impact is fossil fuel use by tractors and transport vehicles, which represents 48% to 77% in the impact categories HTP, ODP, ADP and POCP. The energetic and environmental performance of *B. carinata* [39,120] can be improved by use of biofertilisers.

Agronomic aspects of *B. carinata* and *B. napus* were compared in Italian conditions [39]. *B. carinata* has the capability to optimise the energy used for the primary cultivation process. By shifting the *B. carinata* cropping system from high to low input the energy output/input ratio increases, as opposed to *B. napus*. The superiority of *B. carinata* energetic yields in low input systems is also evidenced by the ratio between the agronomic input and the corresponding grain yield. The oil content of *B. carinata* seeds (33.0 wt%) is slightly lower than *B. napus* (38.9 wt%). The high level of glucosinolates (Gls) typical of *B. carinata* meal precludes its direct use as an animal feed, unless the glucosinolates are extracted. Allocations were not made. Glucosinolates are secondary plant metabolites that occur in all Brassica-originated feeds and fodders. The Gls content is generally higher in rapeseed meal (RSM) varieties grown under tropical environment than those in temperate regions. Water extraction, heat and $CuSO_4$ treatments are suitable for glucosinolates detoxification [121].

A comparison of the performance of *B. carinata* oil-derived biodiesel with a commercial Italian biodiesel (Navaol, based on 70% RSO and 30% SNO/SBO) and D-2 petrodiesel (ExxonMobil), conducted as regards engine performance and exhaust emissions, confirmed its suitability as a biofuel. As *B. carinata* biodiesel is characterised by high IV (128 g I_2/hg) and high linolenic acid content (13 wt%) – exceeding EN 14214 specifications – it should be blended. *B. carinata* productivity under low input cropping conditions, associated with the performance of its derived biodiesel, quite similar to commercial biodiesel, makes it an interesting oilcrop. Further work is needed to improve grain yield and to valorise the by-products of the agronomic and industrial transformations.

A comparative study of alternative transportation fuels in Greece only serves as a general input to the country's future energy policy but does not permit to gain insight in local rape biodiesel production [81]. Distribution of biodiesel in Greece started in December 2005. Greek biodiesel production reached a level of 77 kt in 2009 (down from 107 kt in 2008) or approximately half the EU 5.75% target of 2010. The main locally produced vegetable oils are sunflower, cottonseed and soybean oil. Raw materials for the Greek biodiesel industry with an excessive nameplate capacity of 662 kt (2010) are mainly rapeseed and soy seed oils (imported for 70%).

In an LCA comparison of biodiesel from rapeseed, sunflower and soybean oil the origin of the data was not made clear; consequently, only generic conclusions can be derived [83]. In order to reduce the environmental impact of biodiesel the main attention should be focused on the agricultural oilcrop production stage. In terms of land-use (and consequent agrochemicals application) rapeseed and soybean cultivation is to be preferred over sunflower for biodiesel production.

5.4. North American conditions

Canola cropping conditions are considered ideal in Western Canada. Biodiesel produced from Canadian canola is significantly different from European rapeseed biodiesel. Canadian canola production for conversion to biodiesel presents unique life attributes, including:

- High rate of hybrid adoption (85% in 2009).
- No need for pH adjustment through addition of lime due to the alkaline nature of most production soils (*cfr.* EU default value for lime of 6.1 kg/t rapeseed).
- Energy efficient production system with low diesel fuel requirements and high adoption rate (75%) of low or no till agriculture.
- Efficient nitrogen fertiliser production industry in Canada with a low application percentage of nitrate fertilisers.
- Use of ammonium type fertilisers with lower GHG emissions profile.
- Low N_2O emissions in the primary canola production areas with low annual precipitation (dryland production).

Ammonium nitrate (AN) and calcium ammonium nitrate (CAN) are the dominant types of nitrogen fertiliser in Europe with GHG emission intensity about double that of urea [122]. On the contrary, the low rate of use of AN and urea ammonium nitrate (UAN) fertiliser (49 kg N/t) in Canada reduces the GHG emissions of canola production compared to rapeseed production in Europe. Moreover, the Canadian fertiliser industry is reputed being the most efficient in the world [123]. The application rate of herbicides is declining as a result of herbicide-resistant canola [124]. In 2000 the application rate was 0.3 l active ingredient (a.i.)/ha for GM crops and 0.9 l a.i./ha for conventional seed. Energy consumption for canola cultivation is low. In Canadian conditions the transportation distances (mainly rail) are rather high (typically 2000 km). An LCA model was developed based on the system expansion process for allocation credits to by-products [37].

Canola seed is traditionally crushed and solvent extracted using refined hexane. Cooking serves to thermally rupture oil cells and adjusts the moisture of the flakes. In Canada the cooking cycle usually lasts 15–20 min. at 80–105 °C. In some countries, notably P.R. China, cooking temperatures of up to 120 °C have traditionally been used. All of the Canadian canola crushing plants

use natural gas as their thermal energy source. Total canola crushing energy requirements are 2.75 GJ/t oil produced. Canadian production methods result in a crop with a good energy balance and low GHG emissions profile. The total energy balance for canola biodiesel of 4.434 J/J is slightly better than that for petroleum diesel (3.923 J/J). The biodiesel co-production system does not use a large amount of biofuels. The biodiesel co-product glycerine displaces a significant amount of electricity and when the fossil energy only is included, this co-product credit is lower. The net fossil energy ratios (which only consider the fossil energy consumed in the production process) are 3.933 J/J for biodiesel and 4.359 J/J for petrodiesel.

The specific agronomic practices employed by Canadian canola producers have a significant impact on GHG emissions. Very little canola cropland is irrigated. Irrigation has a negative impact on the energy consumption and N_2O emissions but a positive impact on crop yield. A significant portion of the GHG emissions associated with agriculture is related to the release of N_2O resulting from the breakdown of nitrogen fertilisers and crop residues. The average carbon intensity of nitrogen fertiliser in Canada is 2.8 kg CO_2 eq/kg N (*cfr.* 5.88 kg in EU LCA models). N_2O emissions in Canada are 60–75% of European values.

GHG emissions for the production of a fuel are informative but are biased in case of biofuels because by definition the biogenic CO_2 emissions are not counted for the production of a biofuel and thus the fossil fuel results in having significantly higher emissions when produced and burned compared to many biofuels. Canola biodiesel, however, is one of the biofuels that have lower emissions for both the production and combustion stage compared to fossil fuels. The fuel life cycle emissions from the production and use of biodiesel include the benefit of the biogenic emissions. Canola biodiesel reduces the life cycle GHG emissions by 90.1% compared to fossil diesel (0.0015% S), namely from 1428.7 to 141.2 g CO_2 eq/km. Expressed differently, the GHG emission reduction per litre of canola biodiesel produced and consumed amounts to 2.97 kg CO_2/litre of biodiesel [37]. Canadian canola biodiesel shows very large GHG emissions reductions which are a result of the unique characteristics of the local agricultural practice, not easily found elsewhere, and the LCA modelling framework (system expansion process). Taking into account the cumulative effects of the improved nitrogen fertilisation, low Canadian N_2O emission factor, absence of lime to increase the soil pH and improve the yield, correlation of fuel consumption to field area rather than crop production, and build up of soil carbon in the Canadian agricultural area due to the reduction of summerfallow and the increased adoption of no tillage management practices account for the following comparative life cycle GHG emissions (in g CO_2 eq/GJ, HHV): Canadian canola biodiesel 5065, European canola biodiesel 47,189, and petrodiesel 20,444. Also Reijnders et al. [16] indicated a similar relative performance of European biodiesel and conventional diesel.

Smith et al. [38] have compared the energy balances of biodiesel production from typical canola and soybean agricultural practices in Canada using a system expansion approach. Per unit seed yield, farm production energy inputs for canola are about three times higher than for soybean (Fig. 4), mostly because of higher nitrogen fertiliser requirements for canola. Energy required by processing and oil extraction, per unit oil, is higher for soybean. Differences in processing the oilseeds include drying of soybeans since the ideal moisture for flaking is less than that for storage; for canola press and hexane extraction is used as compared to only hexane extraction for soybeans. Energy required for transesterification per unit extracted oil is the same for both sources but for canola larger amounts of oil need transesterification, (*cfr.* Fig. 4). The ratio of biodiesel energy produced per energy input was similar for both crops, namely 2.08–2.36 for canola and 2.12–2.41 for soybean (tillage dependent). Soybean requires less energy inputs, but also produces less oil than canola, for a given weight of seed. The estimated life-cycle energy inputs for canola (6.2 GJ/ha) and soybean (3.9 GJ/ha) – both for no-tillage systems – were similar to those reported by Mortimer et al. [56] for biodiesel from oilseed rape in the United Kingdom but lower than those reported for soybean by others [17,18]. The lower estimate reflects the absence of liming and the use of lower tillage intensity; also energy used by farm personnel and in the processing industry was not included. Hill et al. [17] estimated this energy consumption to be about 34.2% of total biodiesel energy input. The estimated energy inputs were far below values reported by Venturi et al. [60] for agricultural practice in Italy. The more favourable energy ratio reported by $(S\&T)^2$ Consultants, Inc. [37] for Canadian canola (4.43 J/J) partly reflect the assumed (most recent) enhanced crop yields (1.82 t/ha *vs.* 1.39 t/ha) and lower crushing energy requirements (1.18 *vs.* 1.66 GJ/t seed). The value of 1.18 GJ/t of canola crushed, or 2.75 GJ/t oil produced, was based on a survey of ten plants in North America, all using natural gas as their source of thermal energy. The continual adoption of new technologies in farming, oil processing, and for biodiesel conversion improves energy ratios, as also reported for soybean [125]. For zero tillage canola, a total of 8.31 GJ/t canola was expended to grow and process the seed as compared to 4.53 GJ/t for soybean. For a zero

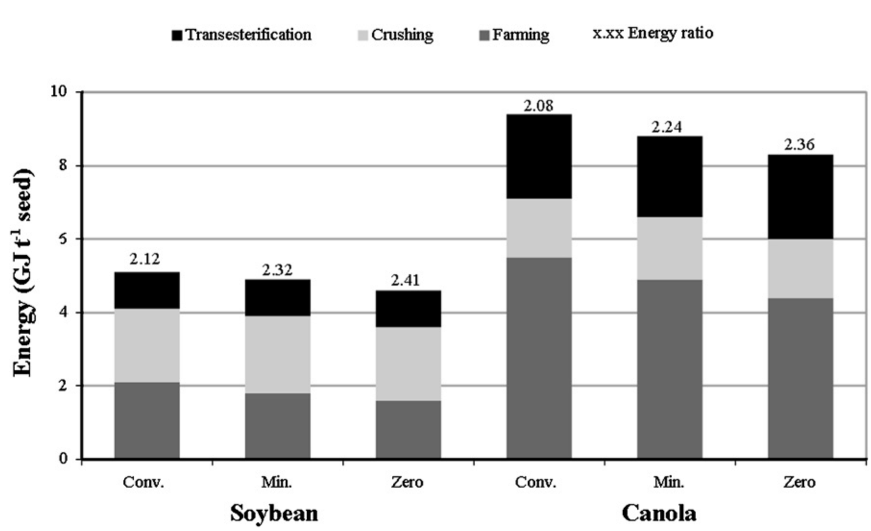

Fig. 4. Energy input and ratios for biodiesel production per tonne of soybean or canola seed for conventional, minimal and zero tillage conditions. After Ref. [38].

tillage farm plus crushing/extraction the energy input would need to increase to 17.9 GJ/t for canola (+196%) and to 10.9 GJ/t for soybean (+163%) before the output/input energy balance for more energy intensive farming and processing systems would decline to a break-even point. An allocation of energy used by individuals involved in producing and processing canola and soybean would still result in a positive energy balance for the biodiesel production. The energy balance also remains positive without co-product allocation. The co-product allocation also affects the calculated energy balance. If no energy is allocated to protein meal, the output/input energy ratio declines to 1.91–2.16 for canola and to 1.52–1.70 for soybean, The relatively smaller decline for canola reflects a lower percentage of energy allocated to canola meal (11.9%) than to soybean meal (36.7%). However, the energy balance remains positive without co-product allocation.

5.5. South American conditions

Major oleaginous local crops for future biodiesel production in Chile are rapeseed and sunflower, without the need for competing with crops grown as a food source. Rapeseed, cultivated in Central-Southern Chile with a temperate climate, is grown in crop rotation (every four years) in non-irrigated andisol-type soils under conventional or (mostly) no-tillage conditions and yields 3.5 t seeds/ha [31], *cfr.* 4.1 t/ha in Germany. At present, the main use of Chilean rapeseed is as a feed for the national industry of salmon for export. Sunflower is grown in irrigated inceptisol-type soils in warm Central Chile using crop rotation under conventional tillage (soil inversion, plowing and harrowing); average seed yield 2.2 t/ha. The energy demand for RSO is 4.9 GJ/t seed, 30% less than that of SNO. The energy balance ratio is 5.0 for RSO and 3.5 for SNO. In agricultural conditions in Germany [35] and Italy [39] rapeseed crops with application of mineral fertilisation presented an energy demand of 3.3 and 7.6 GJ/t seed; values depend on the rate of application of agrochemicals and the fuels and electricity used in the farm (highly depending on the energy mix of a country). The stages of extraction of raw materials and fertilisers production have the highest energy demand (92%) and also carry the highest environmental impacts, with a contribution of $>80\%$ in eight categories. For rapeseed the contribution of mineral fertilisers (including their field emissions, in particular N_2O) is between 74% and 99% for all impact categories considered (ADP, AP, EP, GWP, TETP, HTP, MAETP, ODP, POCP, RAD) with the exception of FAETP where the contribution of fertilisers is only 10% [85]. Similar findings were reported for cropping systems elsewhere [52,120,126]. Fertilisers contribute 93% of the CO_2 eq emissions of rapeseed production and 83% of sunflower, in agreement with Refs. [30,52,91]. Rapeseed oil production shows better environmental performance than sunflower oil in almost all impact categories except HTP and POCP, as well as lower water consumption (40,000 kg/t seed, or four times lower than SNO with its higher evapotranspiration conditions). The greatest differences in the environmental impacts of the crops are in the categories FAETP and TETP (ascribed to application of the herbicide linuron) and POCP (resulting from emissions from diesel combustion, associated with higher diesel consumption in conventional tillage). In Chilean conditions, the better environmental and energy performance of rapeseed is mainly a result of using less toxic herbicides and the lower level of agricultural inputs per unit of crop as compared to sunflower.

As in order to supply Chile with biodiesel in the short term rapeseed and sunflower would be cultivated on existing local agricultural land, direct LUC (dLUC) was considered almost null. However, since both crops may induce land-use change, two dLUC scenarios were evaluated, namely from severely degraded grass-land to cultivated land (scenario 1) and from improved grassland to cultivated land (scenario 2). The dLUC leads to a change in soil and aboveground carbon stock. Results show that GWP ranges from 640 kg CO_2 eq/t seeds (scenario 1) to 1070 kg CO_2 eq/t seeds (scenario 2) for rapeseed production. Depending on field N_2O emissions and dLUC scenarios, variations in GWP for rapeseed may range from −70% to +95%. Indirect LUC was not addressed by lack of data. If the production of Chilean energy crops leads to conversion of land to cultivated land of biofuels production, use of degraded grasslands is desirable as this might contribute to reduce GHG emissions of the crops.

In Chilean conditions, rapeseed has a better environmental profile than sunflower, which can be ascribed to: (i) use of less mineral fertilisers per unit of seeds produced; (ii) application of less toxic herbicides; (iii) use of no-tillage system; and (iv) lower water footprint. Other sources of fertilisers should be evaluated environmentally, such as locally produced nitrogen fertilisers or biofertilisers (*e.g.* local livestock manure, sewage sludge). As the crop cultivation stage makes a most significant contribution to the environmental impact, it is likely that a comparative LCA of rape and sunflower biodiesel in Chile will reflect the same relative environmental performance.

5.6. Asian Pacific conditions

Tate et al. [36] have described an LCA study for the production of canola biodiesel using New Zealand (Southland) non-irrigated crops and production facilities, and economic, energy and weight allocations. Canola yield in New Zealand (3.2 t/ha/yr) is similar to rapeseed yields in Germany or France but higher than those in the UK (3.03 t/ha/yr) and far exceed those for canola in Canada (1.82 t/ha/yr). The higher agrochemical inputs in the UK (297.1 kg/ha *vs.* 160 kg/ha in New Zealand (NZ)) are attributed to the generally higher use of nitrogen fertiliser in the UK. Higher fuel use in NZ indicates less fuel efficient machinery and differences in farming practices. The overall difference in CO_2 eq emissions in the crop production stage, approximately 125 kg CO_2/t biodiesel less for NZ as compared to UK, is attributed to lower fertiliser use and lower carbon intensity of fertiliser production in NZ. Many GHG emission factors for NZ are considerably lower than in the UK, which is mainly due to a higher ratio of low carbon or renewable electricity generation (*e.g.* hydrogeneration) in NZ. Without rapeseed meal credit GHG emissions for drying, extraction and refining of rapeseed are 20% higher in the UK than for NZ. Total GHG emissions for conversions (oil extraction) are 381 kg CO_2/t biodiesel lower for NZ as compared to UK data, which is mainly on account of the higher meal credit given in NZ data. GHG emissions for transport of rapeseed oil from extraction facility to the biodiesel plant and from there to the blending facility were ignored. The relatively low GHG emissions for the biodiesel production stage in NZ when compared to the UK are mostly related to the lower GHG emission factor for methanol (due to NZ electricity) and differences in allocation to glycerine. Using the GHG emissions from 3.2 t/ha/yr yield canola biodiesel without a glycerine credit leads to 42% GHG savings compared with fossil fuel (3.8 kg eq. CO_2/kg fossil diesel) [127]. This is comparable with the well-to-wheels GHG emissions for tallow-based biodiesel.

Another LCA of rapeseed biodiesel from non-irrigated cropping in Southland (NZ) using typical arable tillage techniques (3–4 passes) and a fertiliser application of 160 kg N/ha/yr has taken into account future improvements in crop yield (from 3.2 to 3.9 t/ha), *cfr.* Table 22 [86]. A rapeseed to rape oil conversion rate of 39.9% was assumed with production of 1.6 kg meal/kg BD. Straw was not included in the evaluation. The energy requirement for cultivation is 11.0 MJ/kg BD (with meal credit) or 15.2 MJ/kg BD (no meal credit).

Table 22
Primary energy and greenhouse gas emissions from Southland rapeseed biodiesel (BD).

Yield (t/ha)	Primary energy (MJ/kg BD)	Energy ratio[a]	Primary energy reduction (%)[b]	GHG (kg CO_2 eq/kg BD)	GWP reduction (%)[b]
3.2	21.5	1.85	55	2.03	47
3.9	19.5	2.04	59	1.76	54

After Ref. [86].

[a] Output/input.
[b] Compared with fossil diesel use.

Table 23
Breakdown by process of the gross primary energy (HHV) and GHG emissions for biodiesel from rapeseed.[a,b]

Process	Primary energy (MJ/kg BD)	GHG (kg CO_2 eq/kg BD)
Cultivation	11.0	1.49
Oil extraction	2.5	0.25
Oil refining	0.3	0.04
Transport	0	0
Biodiesel production	7.7	0.25
Total	21.5	2.03

After Ref. [86].

[a] Base scenario: yield 3.2 t/ha.
[b] Including meal credit.

Table 23 shows the gross primary energy of biodiesel at the production plant gate, taking into account credits for rapeseed meal (on mass allocation basis). Based on a higher heating value (HHV) of RME of 40.07 MJ/kg BD [128], EROI of Southland rape biodiesel is 1.85. Total GHG emissions associated with biodiesel (2.03 kg CO_2 eq/kg BD) correspond to a 47% reduction in GWP compared with use of fossil diesel. The GHG emission results are similar to those reported in a previous well-to-wheels study promoted by General Motors and others [105] for various fertiliser application rates using comparable LCA methodology. The estimate of field emissions requires further investigation. In comparison, for tallow-derived biodiesel calculated reductions in primary energy and GWP are 58% and 49%, respectively, without a glycerine credit [127]. These values are similar to those for rape biodiesel in the low- and high-yield scenario (Table 22). Tallow is a by-product of livestock production and is only allocated a relatively small fraction of the farming-related primary energy and GHG emissions, quite the opposite of rapeseed. On the other hand, the extraction and refining process is far more energy intensive for tallow compared with that of rapeseed.

P. R. China is a main producer of rapeseed. There are three kinds of rapeseed on the Chinese market, namely *Brassica campestris*, *B. juncea* and *B. napus* (imported). Rapeseed is currently the main raw material for its young biodiesel industry [129]. Biodiesel consumption has grown from 60 kt in 2006 to 0.2 Mt in 2010 with a forecast of 2.0 Mt/yr by 2020. At present only about 700 kg of biodiesel can be produced from a hectare of rapeseed harvest in China (*cfr.* 1048 kg in Sweden) [52]. Due to its low rapeseed yield (1874 kg/ha in PRC *vs.* 2670 kg/ha in Sweden) and low oil content (37% *vs.* 45% in *B. napus*/Sweden) [52,130], lower energy efficiency in Chinese production of nitrogen fertilisers than in developed countries and excess use of fertilisers by Chinese farmers, the overall energy cost of rape biodiesel production in China is estimated at 27.9 GJ or 1.1 times the biodiesel energy content (25.4 MJ), corresponding to a negative energy return [19]. The energy balance for biodiesel in China with its low rapeseed yield is thus quite different from that of economically developed countries with higher rapeseed yield. In Chinese conditions, rapeseed crop production accounts for the largest share of 64.0% in the total energy cost, industrial conversion 33.2%, wastewater treatment 1.6% and transportation 1.2%. Nitrogen fertilisers make up for almost 68.3% in total energy cost of the agricultural crop production stage, due to heavy usage and high embodied energy intensities. China requires higher yield rapeseed species as well as better fertiliser management before domestic rape biodiesel becomes a sustainable biofuel. The energy efficiency to produce nitrogen fertilisers remains remarkably lower than those in developed countries and could benefit from the adoption of more advanced technologies.

5.7. Global conditions

Using a world data set, Harding et al. [88] have focused on the biodiesel catalytic production technology by comparing five alkali (NaOH) and enzyme (*Candida antarctica*) catalysed flowsheet options for continuous production of rape biodiesel using both methanol and ethanol (Table 24). The alkali-catalysed process was based on the approach of Zhang et al. [131]. There are no industrial-scale processes for biodiesel based on enzymatic transesterification. Alcohol recovery was taken into account. Burden allocation was carried out on the basis of mass ratio. LCIA (case 1) indicates large impacts in marine aquatic toxicity (MAETP) and, due to rapeseed farming impacts, eutrophication (EP). Also abiotic depletion (ADP), global warming (GWP) and acidification (AP) show significant impacts. Considering the high energy contribution of the farming process (including fertiliser production) and other energy requirements from natural gas, diesel and heat oil, as well as the impacts associated with steam and methanol production, milder process conditions are expected to improve LCA results (case 2). Excess alcohol recovery is required to minimise waste. Energy needs are reduced by reducing methanol recovery (case 3). To further improve LCA results, ethanol was evaluated for comparison (cases 4 and 5 *vs.* cases 1 and 2). Ethanol is renewable and has suggested advantages due to being environmentally based and CO_2 natural, making it a promising alternative to methanol. In the lipase-catalysed route, alcohol recovery is eliminated completely since a high alcohol concentration can inactivate the enzyme. Enzymatic methanolysis is environmentally more favourable than alkali-catalysed transesterification (case 1 *vs.* 2) with improvements in all ten impact categories considered (on average by 8%), with particularly large gain (37%) in terrestrial ecotoxicity (TETP), mainly due to the removal of HCl from the bio-catalysed process. The results reflect the lower steam requirements for heating in the biological biodiesel process. Lipase-catalysed biodiesel production has environmental advantages due to avoided use of chemical catalyst and neutralising acid and operation at lower T, p.

When methanol recovery in the alkali catalyst process was reduced from 94% to 50% (case 1 *vs.* 3) impacts increased in all categories (*cfr.* Table 24), on average by 15%. All recorded toxicity levels (HTP, FAETP, MAETP, TETP) even increased by at least 20%. Mixed LCA results were observed by replacement of methanol for ethanol (Fig. 5), but quantitatively similar for the alkali-catalysed and enzymatic routes. Negative effects of ethanol use are connected with human toxicity (HTP) and fresh water aquatic toxicity (FWATP).

Table 24
Specifications of different biodiesel production process options.

Option	1	2	3	4	5
Catalyst	Alkali	Lipase	Alkali	Alkali	Lipase
Alcohol used	Methanol	Methanol	Methanol	Ethanol	Ethanol
Alcohol recovery (%)	94	–	50	94	–

After Ref. [88].

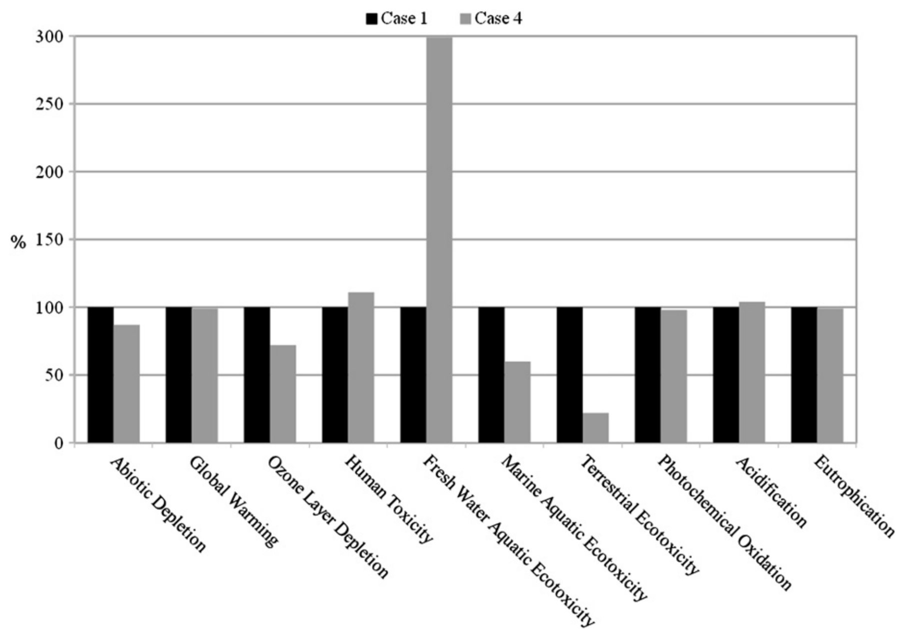

Fig. 5. Comparison of LCA results of alkali-catalysed methanolysis (case 1) and ethanolysis (case 4) assuming 94% alcohol recovery. After Ref. [88].

This was ascribed partly to the use of a sugar-based ethanol LCA module with high coal demand. Terrestrial ecotoxicity (TETP) improves to such an extent that it shows a positive impact (+13%) in case 5 (bio-catalyst and ethanol). The main contributing processes to LCA impacts are similar in all five process options. The impact of methanol production is higher than that of ethanol. In the alkali-catalysed process lower alcohol recovery requires greater flows to give similar product yield and purity. This increases energy needs as well as pollutants and causes a less favourable production route when analysed using life cycle assessment. By application of cleaner production of biodiesel from virgin vegetable oil it is possible to reduce the life cycle emissions of GHGs up to about 5%. However, all technologies lead to higher GHG emissions linked to the biodiesel life cycle (4.1 kg CO_2 eq/kg BD) if compared with conventional diesel (3.6 kg CO_2 eq/kg).

6. Discussion

There are wide variations between different fuel sources in terms of energy used and emissions associated with their extraction and production. A valuable substitute for fossil fuels should provide a net energy gain over the energy sources used to produce it, be sustainable, have superior environmental benefits over the fossil fuel it displaces, be economically competitive and producible in large quantities without reducing food supplies [17]. Common metrics used to compare alternative bioenergy pathways describe energetic performance (energy ratio), environmental performance (emissions, land and water use), economic performance (cost), and social and ecological performance (human welfare, biodiversity) [132]. It is important that the choices of production system and scale are made in a way that minimises the total environmental load.

Both EU's RED and FQD set environmental but no social sustainability criteria. The Fuel Quality Directive aims at promoting the cleanest fuels and obliges suppliers to reduce the life cycle GHG intensity of transport fuel by 6% by 2020 compared with 2010 [12]. Reduction of emissions can be achieved in various ways. As to biodiesel, the efficiency of both the agricultural and processing technologies could be enhanced. The aforementioned LCAs for rape biodiesel give clear evidence and suggest numerous opportunities.

LCA results make difficult comparison. Many new biodiesel production facilities have been set up, at different scales and using different methods of modern manufacture. If agricultural yields, conversion and production are considered, life cycle assessments have reported contrasting results. Some of the results of LCA studies reveal problems due to: (i) incomplete or outdated data; (ii) process simulation software; and (iii) lack of full comprehension of the complexity of the energy system requirements. Lately, research tools have been made available to ensure more correct full-life-cycle analysis.

Various sensitivity analyses determine the influence of the variations in assumptions, method choices, and process data on the results [133]. Significantly different results can be obtained depending on the detail of the input data and the assumptions made to build up the LCA inventory. Disagreement on LCA results are eventually attributable to differing data sets (including data sources and ages) and methodologies. Methodological differences include choices of the system boundaries, functional units, allocation procedures and other assumptions.

A parameter uncertainty propagation study during the full life cycle shows that the level of confidence that rape biodiesel is more environmentally friendly than fossil diesel is 93.1% for non-renewable energy (CED) and 92.3% for global warming (GWP) scores [84]. LCIA results (Fig. 6) indicate that both the non-renewable primary energy consumption and GHG emissions are reduced significantly. The uncertainty of the non-renewable energy (CED) score is mainly determined by natural gas, uranium and hard coal. The global warming impact is reduced by 48% or 0.052 kg CO_2/FU diesel eq. from 0.137 kg CO_2 eq with diesel to 0.085 kg CO_2 eq with rape biodiesel (RME). For biodiesel, the substances contributing most to the uncertainty of the GWP category are CO_2 and N_2O, emitted from regular vehicle operation, followed by rapeseed production (no land-use change considered). Impacts on human health (HH) vary considerably, depending on the use phase, *i.e.* vehicle technology (particle filter, *etc.*).

The German Union for the Promotion of Oil and Protein Plants e.V. (UFOP) has reported a critical life-cycle and cost analysis for a variety of biofuels, including rape oil and rapeseed biodiesel, thereby contributing to a considerable reduction of the bandwidth of literature values [108]. The results for rape biodiesel are

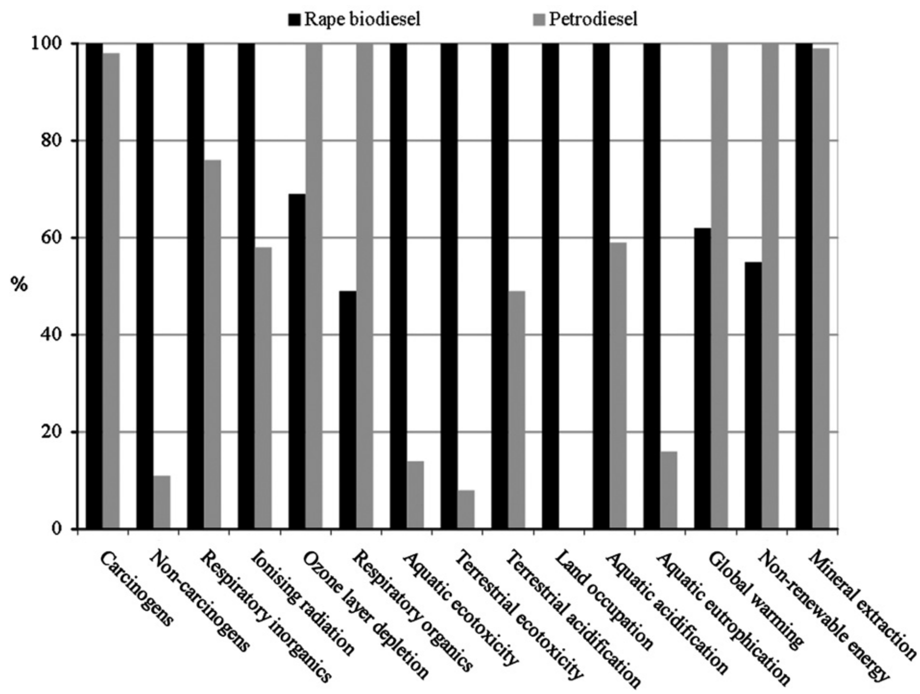

Fig. 6. Comparative midpoint assessment for the full life cycle of rape biodiesel and petrodiesel, relative to the highest score. After Ref. [84].

Table 25
Synopsis of cost and life cycle analysis of rape biodiesel.

Selected criterion	Unit	Literature bandwidth[a]	Restricted value range[b]
Provision costs[c]	€/L fuel eq.	0.38–0.76	0.51–0.73
Biodiesel yield/ha	GJ/ha	40–70	44–52
Total energy yield/ha[d]	GJ/ha	40–124	44–102
GHG reduction	kg CO_2 eq/L fuel eq	0.45–1.80	1.31–1.42
GHG reduction/ha	kg CO_2 eq/ha	640–2560	1600–2000
GHG avoidance costs	€/t CO_2 eq	25–1520	25–380[e]

After Ref. [108].

[a] Based on German literature sources.
[b] Based on calculations of IEE (Institute for Energy and Environment, Leipzig).
[c] 2006 data.
[d] Including by-products (press cake, glycerine).
[e] Related to Germany (2007).

summarised in Table 25. The reduction of the bandwidth of literature values to a justifiable limited range has been achieved by various means, including using a homogeneous general framework as a basis for direct comparison, utilisation of the by-products obtained, correction of divergences resulting from non-consideration of by-products, updating initial values and rejecting evidently non-representative values.

Provision costs referred to 1 L of biofuel equivalent are those costs that arise to provide the amount of biofuels containing the same energy quantity as1 L of the equivalent conventional biofuel (*i.e.* diesel and gasoline). Table 2 shows the heating values of biofuels and allocated equivalent fuels. On a relative scale biofuel provision costs are as follows: rape oil < rape biodiesel ~ bio-SNG (lignocellulose) < biomethane (corn) < bioethanol (cereal) < BTL (lignocellulose) < bioethanol (lignocellulose) [108]. Except for bio-SNG (synthetic natural gas) on average 2nd-generation biofuels show notably higher costs than 1st-generation biofuels such as biodiesel (from plant oil) and bioethanol (from wheat). Account has been taken of credits of the by-products (*e.g.* rapeseed press cake or extraction groat, raw glycerine, electricity). However, it should be considered that some input parameters remain subject to variation. For example, rapeseed or rapeseed oil may be imported in case of feedstock provision for biodiesel production. Also, the use of basically different method concepts is possible, such as centralised and decentralised plant oil provision, process energy supply through conventional energy sources (electricity) or via a CHP plant, as well as different plant technologies.

6.1. Agricultural phase

Various important aspects of agricultural practice are crop rotations *vs.* monocultures, tillage systems and deforestation. Crop rotations determine what crops a particular farm grows. Integrating a legume into a crop rotation is energetically favourable: there is a reduction in the need for N fertiliser by subsequent crops [134]. The tillage system (conventional or reduced) alters energy inputs for machinery use and manufacture, and herbicide inputs. There are various drivers for deforestation but demand for agricultural land is one of the most significant. On a global basis increased demand for land for food and feed will continue to cause a greater proportion of land-use change than the additional land demand for biodiesel.

The main stages in the agricultural phase are cultivation and crushing (oil extraction). Their relative importance in terms of energy requirements and environmental impacts, also in comparison to the industrial transesterification stage, may be seen from Fig. 4 [38], and Tables 7, 9, 11 and 23 [30,56,86]. Cultivation accounts for about 82% of the total impacts and crushing 18%. Production intensity in agricultural cropping is related to the demand for energy. Fertilisers production has the highest energy demand and also carries the highest environmental impacts. A linear relationship has been reported between average agricultural production (t/ha) and average N fertiliser input (kg/ha) between 1970 and 2000 [135]. Increases in rapeseed yield are most likely to take place where the largest crop response is achieved, which will be in fields where the fertiliser application is below average. In

comparison to Canadian canola, European rapeseed agriculture is handicapped by less efficient N fertiliser production with an inferior energy balance and a higher GHG emissions profile [37]. Chinese agriculture suffers from excessive fertiliser use [19]. Tropical agriculture uses pesticides some of which are forbidden in Europe in view of their toxicity. The effects of increased yield on primary energy and GHG emissions are shown in Table 13 for French rapeseed [33] and in Table 22 for NZ rape biodiesel [86]. The lowest energy and emissions savings are reported when all inputs and emissions are attributed to biodiesel (no allocation), whereas the highest values are obtained in case of burning of rapeseed [101,102]. However, straw is mostly left on field. Fuel consumption correlates much better to field area than to crop production. The European default value for diesel consumption in 82.6 L/ha.

After cultivation rapeseed is dried, cleaned and cooled. Rape oilseed is harvested with a typical moisture content of 13 wt% which must be reduced by drying to at most 9 wt% as a requirement for the oil extraction facilities and to ensure stability in storage. Grain drying is identified as a minor energy contributor in the agricultural rapeseed stage, accounting for almost 5% (*cfr.* Tables 6 and 11). Extraction consists of either cold pressing and solvent treatment using hexane (*e.g.* [30,38,52,56,102,103]), or hot pressing and crushing (*e.g.* [57,79,98]). The main currently used vegetable oil production methods involve pressing and extraction by organic solvents. Cold pressing ($T<60\,^{\circ}C$) requires less energy and there are less phospholipids in the oil, which is desirable for biodiesel production. However, 12–14% of oil is left in the cake. Compared to cold pressing, hot pressing ($T=110$–$120\,^{\circ}C$) requires a larger quantity of oil. However, in this case 6–7% of oil is left in the cake even when slow presses are used. The vegetable oil extraction efficiency in small-scale systems is lower in comparison to large-scale systems [102,136]. Using hexane solvent extraction, only 0.1–0.8% of oil is left in the cake, but the phospholipid content is higher [37,56]. Consequently, additional energy consuming oil degumming is then required before transesterification. The oil extraction process also affects the total glucosinolate contents of the meals. Expeller extracted meal contains less glucosinolate than occurs in case of solvent extraction. Dietary glucosinolate have deleterious effects on animals.

There are considerable differences between estimates of the primary energy inputs and CO_2 outputs of rapeseed drying/oil extraction/refining. These are on account of scale, method of extraction, extraction efficiencies and allocations (credits). In the past, the energy required for crushing has been grossly overestimated [79]. Typical, variously expressed, values range from 815 to 2805 MJ/t BD for a modified and conventional biodiesel process, respectively [56], from 1512 to 3896 MJ/t BD for small-scale cold pressing without refining to large-scale extraction/refining, respectively [30], 2800 MJ/t BD (with credits) [86], 1.18–1.66 GJ/t seed [37,38], and 12 MJ/GJ [97].

Effective use of energy in agriculture is important for sustainable agricultural production, to optimise economic return, preserve fossil fuel reserves and reduce air pollution [137]. Detailed knowledge of fossil fuel energy use in agricultural systems is essential in developing cropping practices that utilise limited energy resources more efficiently.

Energy analysis provides important information on cropping system properties. There is no standardised methodology for determining the optimum level of energy input per area of agricultural land or unit output. To determine the energy efficiency in crop production, different energetic parameters are available, such as energy balance or energy gain (net energy output), energy intensity and output/input ratio (EROI). A maximum energy gain is desirable when land is used to produce renewable energy or when land area for growing crops is limited. Energy intensity and output/input ratio are measures of the environmental effects associated with crop production. Therefore, these parameters can be used to determine the optimum intensity of land and crop management from a ecological point of view. The highest energy output/input ratio were observed for low production intensities and decreased with increasing production intensity [35]. Energy indicators depict the efficiency of production systems, allow comparison of different production intensities and are a suitable supplement to economic analysis [138].

6.1.1. Energy conservation in agriculture

Although sunlight energy is the primary input to crop production, energy balance sheets in agriculture are mainly determined by the support energy (fossil energy inputs of mineral fertiliser and fuel), which are highly correlated to the production intensity. Fertilisers application rates depend on oilcrop and location. Nitrogen is the most limiting nutrient for crop farming [139] and optimum N management is the most important factor for energy conservation. Increased application of N fertilisers results in increased growth rate and, hence, increased energy outputs per area. Among all inorganic agricultural fertilisers production of nitrogen fertiliser represents the largest component of total energy input in most cropping systems [35,59,140,141]. In developed countries, the relative share of mineral N fertiliser amounts up to 55% of the total energy input for a high-input system of winter OSR production [141], but can be reduced to approximately 30% at lower input level. Rathke et al. [35] reported a range from 20% to 51%. The total energy consumption is highly variable depending on the rate of N fertiliser used. Typically, there is a clear linear relationship between increasing N fertiliser rates and the total energy input.

The energetic effectiveness of winter oilseed rape production has been investigated by several authors [35,89,102,141–143]. Alternative fertiliser (mineral, organic) and previous crop management significantly affects the total energy input and energy efficiency of cropping systems. The energy efficiency of winter OSR responds mainly to different N management strategies. The optimal N application rate of winter OSR depends on the scope of production. For high energy output and energy gain, high rates of N are required, whereas only small N rates are essential for low energy intensity and no N results in the highest output/input ratios [35]. Maximum net primary energy savings per unit land area been reported to occur at a N fertiliser application rate of 184 kg N/ha/yr [89]. Several publications have dealt with the effects of previous crops on the energy balance of a crop [35,134,144]. The preceding crop effect is particularly relevant for rapeseed, typically 32.5 kg N/ha/yr [34] but values of 90 kg N/ha/yr have been mentioned [145]. Pea and barley have been evaluated as previous crops to winter oilseed rape [35,144]. Legumes are excellent sources for biological fixation of N in agriculture [146]. It is well known that the quality of N fixation is directly related to pea growth. To reduce energy inputs, high yielding legumes should be integrated into crop rotation as a substitute for N fertiliser. Management systems with legume as a previous crop have a greater output/input ratio than those with a cereal as the previous crop [147].

In addition, organic fertilisation can substitute for mineral fertilisers and reduce indirect energy requirements [35,140,148]. It has been observed that OSR yields are lower with organic fertiliser than with mineral N fertiliser [35]. Similarly, also grain corn was cultivated more successfully using inorganic N fertiliser than with manure [140]. As the concentration of N in slurry is much lower than in CAN much more organic fertiliser has to be applied to the field to meet the target level of N fertilisation. Being a by-product of livestock production, manure is not always considered explicitly as an energy input. Depending on the method of balancing, the energy input achieved in manure

treatments is lower than that of inorganic fertiliser. For example, McLaughlin et al. [140] reported energy savings from 36% to 52% when manure was substituted for inorganic fertiliser in corn production. No savings could be determined for OSR by Rathke et al. [35] who explicitly considered manure as an energy input. Most of the biological waste is currently not yet used on biofertilisers in agriculture. For the production of EU compliant biofertilisers it is possible to use sewage sludge, manure, slaughterhouse waste (meat bone mass). The biofertiliser production process does not require additional electricity or fossil fuel energy. EROI in organic agriculture is better than in conventional agriculture [134]. Energy consumption in agriculture would also be reduced by implementing advanced chemical seed preservation technologies, which would substitute the usual seed drying [59]. These technologies are not yet widely practised. Total crushing energy requirements can be reduced by optimisation of the cooking cycle (T, t, thermal energy source) [37]. A better energy ratio is also obtained by biotechnological oil extraction.

Apart from fertiliser, the direct energy input due to fossil diesel consumption is the second most important input factor ranging from 17% to 39% [141] and from 21% to 46% [35] for winter OSR. The energy required to grow crops depends on the tillage system. At lower N rates, diesel contributes a greater percentage of total energy input. In contrast to fertiliser and diesel, the factors seed material, plant protection and machines are less important. Although pesticide manufacturing tends to be energy intensive, the contribution to the total energy input is small ($<10\%$) because of the generally low application rates per unit land area.

The energy balance is always favourable for rapeseed (Tables 13 and 18), but less so for its methyl ester (Tables 13 and 19) [60].

6.1.2. Environmental performance

One of the most widely used metrics for comparing environmental performance of bioenergy pathways is the GHG emissions (or equivalents) per unit energy (kg CO_2 eq/GJ). This metrics allows measuring the whole system performance but is less straightforward for systems producing both energy and non-energy products, as in case of rape biodiesel. In practice, the amount of GHG saved is not limited by the amount of fossil fuels replaced but by the amount of land available [149].

Agriculture is a source of considerable emissions and currently accounts for almost 12% of human-caused GHG emissions (mainly CO_2, CH_4, and N_2O with relative IPCC emission coefficients of 1, 23 and 296 CO_2 eq). The main components of agricultural emissions outside of land-use change are N_2O and CH_4. Nitrous oxide mainly comes from field emissions (denitrification and nitrification) and from production of N fertilisers. Increased reliance on nitrogen-based fertilisers has caused a rise in atmospheric N_2O levels [150]. Carbon is released from both biomass and soil by conversion of forest, shrub, and grassland to cropland. Key issues affecting soil carbon exchange and thus the GHG balance of biodiesel are: (i) land-use; (ii) geographic region (climate and soil type); (iii) soil management practices (full-, reduced or no-tillage); and (iv) carbon inputs to soils (return of crop residues to the field, manure carbon input cropping, *etc.*). A large degree of variability exists concerning the management practices and input levels. Development of agricultural systems needing low fossil energy inputs while maintaining high output helps to reduce agricultural CO_2 emissions [151].

A main argument for the production and use of RME as a biofuel is its potential to reduce the emissions that contribute to global warming and one of the main objectives of the establishment of energetic crops in the EU is the fulfilment of commitments to the reduction of greenhouse gases [119]. The most significant contributions to GWP from rapeseed oil as a feedstock for biodiesel come from rapeseed cultivation [56,64]; *cfr.* also Tables 6 and 7. In the most favourable case (no land-use effects) RME can save 64% of the fossil energy and 53% of the GHG emissions required for petrodiesel [152]. Actually, direct GHG emissions from conventional diesel are usually underestimated if one also takes into consideration unconventional oil extractions (oil sands) and collateral damage from oil spills. The cumulated non-renewable energy demand (CED) correlates with the GHG emissions. Carbon dioxide comes from production of fertiliser, traction and from transportation of agricultural inputs and outputs. Irrigation, which has a positive impact on crop yield, has a negative effect on the energy consumption and N_2O emissions.

In the production of biodiesel, biogenic N_2O emissions are associated with the cropping of rapeseed or other biodiesel crops when conversion by microorganisms of fixed N-compounds takes place. Fixed nitrogen is added to the agricultural fields by way of fertiliser, manure, harvest residue biological fixation and atmospheric deposition. The size of the N_2O emission coefficient is subject to fierce debate and has been indicated to range from 1.25% [153] to 3–5% [154] of added fixed nitrogen. Local conditions may significantly affect conversion rates. Agricultural N_2O emissions are very seasonal and depend on crop type, soil moisture and temperature, as well as on the rate and form of applied fertiliser [155]. N_2O emissions from different fields are extremely variable (by orders of magnitude) depending on soil composition and farming practices. Little information is available about the nitrous oxide emissions emanating from fallow areas and these are often ignored. However, in extreme cases N_2O emissions from set-aside land can be as high as those from areas under agricultural use [156]. Nitrous oxides not only contribute to global warming but also cause ozone depletion.

As to global warming, key uncertainties derive from the effects of climate-active species (also including NO_X, CO, SO_X, aerosols), poorly characterised emissions from agriculture (in particular N_2O), soil carbon sequestration and allocation methods. Soil carbon sequestration *cq.* release is highly site specific, dependent on soil type, prior land-use application, and agricultural practice.

As the crop cultivation stage makes the most significant contribution to the overall environmental impacts it is important that the choices of production system and scale are made in a way that minimises the total environmental load. Although GHG emissions from the production and use of fertilisers have increased with agricultural intensification, those emissions are far outstripped by the emissions that would have been generated in converting additional forest and grassland to farmland. Yields intensification has lessened the pressure to clear land and reduced emissions by up to 13 Gt CO_2/yr since 1961 [112]. High-yield agriculture has slowed down the pace of global warming. Reduction of GHG emissions from feedstock production (measured as t CO_2 saved/unit energy) may be achieved in various ways such as reducing the inputs to production in a low productivity scenario requiring a high land and water footprint. On the other land, net GHG emission reductions per land unit might also be achieved by a high-input (fertilisers, *etc.*), high-output system leading to higher productivity. The size and cost-effectiveness of this carbon reduction is striking when compared with other proposed mitigation options [50]. Funding agricultural research ranks among the cheapest ways to prevent GHG emissions.

Although the environmental focus is mainly on savings of non-renewable energy resources and GHG emissions on a global scale, production of biomass is often also associated with adverse environmental effects such as eutrophication of surface and ground water on a regional level. Ecotoxicity problems in rapeseed cultivation are mainly on account of fertilisers. Approximately 50% of the impacts of rape oil cultivation in Europe stem from nitrate, phosphate and cypermethrin emissions. The most worrying effect of fertilisers is eutrophication. Fertilisers also disturb the acid–base equilibrium in the soil leading to acidification. The agricultural sector should be

careful in its fertilisers choice and use. Improved soil cultivation practices, *e.g.* extensive and low- or non-tillage farming, can reduce fertiliser losses substantially by: (i) reducing the total amount of fertilisers applied; (ii) improving the seasonal management of fertiliser application; (iii) reducing overall soil erosion from agricultural land; and (iv) precision farming [75]. Use of pesticides in rapeseed cultivation is relatively low. Production of RME increases acidification compared to petrodiesel, but fossil energy consumption also causes acidification. Acidification is even increased if biomass is used to replace fossil resources used for the production of energy (power/heat) and transportation fuels. The specific acidification potential is largely caused by SO_X and NO_X emissions resulting from incineration processes. Ammonia emissions from manure application are a source for acidification [157].

There is a fundamental trade-off between local and regional environmental impacts and global impacts. Rapeseed has a relative low water footprint (much better than sunflower), which is favourable for its environmental profile [85]. The EU RED requires that biofuel feedstock must not be grown on land with high biodiversity value. Negative biodiversity impacts are high for rape. Most of the potential environmental impacts are evitable and can be limited.

6.2. Industrial phase

Biodiesel plants can be co-located at the oilseed crusher/extraction/refining plant [56] or they can be stand-alone facilities at a different location [30]. There are numerous examples of both business models. Industrial biodiesel processes are well established. Biodiesel is conventionally produced by transesterification of vegetable oils or animal fats using an alcohol (usually methanol) and a catalyst (alkaline or acid) yielding a mixture of fatty acid alkyl esters and the co-product glycerol. The process generally uses pre-extracted oil as the raw material, which is usually produced by pressing the oil-bearing seeds, eventually followed by solvent extraction of any remaining oil. Production of 1 l of biodiesel requires 0.88 kg of virgin vegetable oils. Biodiesel energy use typically amounts to 0.032 kWh/L of electricity and 20.2 L NG/L biodiesel. In addition to methanol various other chemical inputs are required (*e.g.* $NaOCH_3$, NaOH, HCl, H_3PO_4, citric acid). The biodiesel production process produces 0.106 kg/L glycerine and 0.002 kg/L fatty acids. The major steps of the production process involve reaction (catalytic transesterification), methanol recovery, separation of biodiesel from the glycerol, biodiesel purification, and glycerol purification.

In most LCAs the conventional alkali-catalysed transesterification has been considered. Homogeneous and heterogeneous catalytic transesterification were compared for French rape biodiesel production [33]. Heterogeneous transesterification leads to a decrease in EROI. Most heterogeneous catalysts are only active at higher p, T, thus leading to an enormous increase in investment and running costs. Enzymatic methanolysis (not commercial) appears to be more environmentally favourable than alkali-catalysed transesterification [88]. At the same time, mixed LCA results were reported for replacement of methanol for (renewable) ethanol. However, the ethanolysis step is less energetically favourable and less cost effective [58,158], *cfr.* Table 26. Use of oscillatory flow reactors is believed to lead to lower operating costs and investment [159].

More efficient biodiesel process designs must be developed in order to enhance the profitability of biodiesel production. To this extent, Myint [160] has simulated four different process configurations for the product separation stage. The recommended process design consists in separation of biodiesel and glycerol first, with removal of methanol next, followed by water washing.

Table 26
Comparison of methanolysis and ethanolysis of vegetable oils and fats.

Process parameters	Methylation	Ethylation
Alcohol consumption (kg) per 1000 L biodiesel	90	130
Alcohol costs (US Cts/gal)[a]	103	310[b]
Required excess alcohol (%)[c]	100	650
Recommended reaction temperature (°C)	60	75
Reaction time (min)	45	90

[a] US contract price (FOB) (5 May 2006).
[b] Industrial (99%).
[c] Recoverable by distillation after the reaction.

Biodiesel plant scale is another process variable and the effects of large-scale (>100 kt/yr) and small (farm)-scale (<10 kt/yr) plants have been compared in UK conditions [30] as well as in Swedish conditions [52]. As cultivation is the dominating step regarding environmental and energy requirements, the effect of different industrial production scales on the whole life cycle of rape biodiesel is small. However, production costs are lowest for large-scale production.

6.2.1. Energy accumulated in biodiesel life cycle

Energy accumulated in biodiesel fuel and its by-products is a relatively fixed value; consequently, the largest influence on the energy balance is made by the energy demands for biodiesel fuel production. The total energy consumption in the RME life cycle is mainly on account of cultivation, oil extraction and transesterification. Energy consumption connected to industrial operations (oil extraction plus transesterification) and transport is directly related to the quantity of seed to be processed, *i.e.* related to grain yields. The same is valid also for output values. Estimates of energy required to process oilcrops vary widely in the literature, reflecting differences in extraction process, age of plant, plant size, transesterification technology, performance, energy sources, system boundaries, and method of reporting energy use. For instance, new soybean crush plants use about 42% less energy than older plants [161]. Differences in processing the oilseeds include the drying and extraction modes. The net efficiency (HHV basis) of extraction of RSO and esterification to RME for a typical capacity – in isolation of the rest of the supply chain – is given as 88% [162].

In cases where oilseeds are shipped to a plant and crushed into oil that is converted to biodiesel onsite, oil transport is usually not included in the baseline inventory. However, many biodiesel plants do not have crushing capability, they purchase oil and have it transported to their plant. The energy required to transport oil to a biodiesel plant is about 0.17 MJ/L (biodiesel share) for 920 km (571 mi) [125]. When adding this energy to the inventory, the fossil energy ratio (FER) decreases.

Various rapeseed oil extraction (cold and hot pressing, solvent extraction) and transesterification technologies are currently used in the production of biodiesel. Oil degumming may eventually be required before transesterification. Energy required for transesterification of extracted oils should be the same for sources with similar free fatty acid (FFA) contents [38]. Higher quality oil and cake can be obtained, with reduced energy consumption and environmental pollution, by using the fermentation hydrolysis principle-based biotechnological oil extraction method, which requires only 2089 MJ/t RME produced, as compared to 2328 MJ by applying the classic cold press technology [59]. Various transesterification technologies, such as use of heterogeneous catalysis [33] or biocatalysis [88] have been evaluated in life cycle assessments.

An average breakdown by agricultural and industrial process steps of the gross primary energy for biodiesel from rapeseed

is as follows: cultivation, 38%; drying/extraction/refining, 18%; transesterification, 40%; transportation/distribution/storage, 4%. However, great differences are noticed (*cfr.* Tables 6, 7, 9, 11 and 23). In particular, the total primary energy input varies widely ranging from 7750 MJ/t BD [56] to about 21,500 MJ/t BD [30,86], where the low value is a result of low-nitrogen cultivation, use of straw as fuel and of biofuel instead of fossil fuel. The total energy requirements for small- and large-scale rape biodiesel production are similar, but show up important differences between the processing steps (extraction, refining and transportation), *cfr.* Table 11 [30]. The energy requirement in the transesterification stage depends much on the methanol recovery, which is less favourable for small-scale processing.

Energy balances (EROI) of RME are unfavourable when compared to perennial crops, meaning the net energy production per hectare is low. In the past in some cases the balance was negative (*cfr.* Table 19); this still applies to recent Chinese conditions [19]. Some other reports have indicated an energy ratio of less than one because the actual energy in the oil was included, as well as the energy to produce the oilseed, while other studies have included the human energy input associated with the production of the oilseed and biodiesel [18,163]. Others did not include the oilseed energy nor human energy [37,38]. For the case of rape biodiesel in Britain, yield of 1 ha of land produced 1.5 t of biodiesel with an energy content of 54,346 MJ and a fossil energy cost of 30,505 MJ for the industrial stages of agricultural crop production, crushing, and transport and processing (EROI = 1.78) [164]. The average fossil energy input for production of rape biodiesel was given as 13.7 MJ/t BD in seven pre-2006 studies, EROI = 2.5 [115]. Also other studies reported an average energy ratio of 2.5 for a range of 1.2–3.7 [165]. A midrange estimate for the life cycle energy ratio of RME was given as 2.29 [59,166]. In another study the mean energy requirement (MJ out/MJ in) for rape biodiesel of 3.58 was compared to 5.29 for used cooking oil (UCO) biodiesel [21]. In the longer term, energy balances and economic performance of RME can be improved to some extent, particularly by using residue straw for efficient heat and power production [162]. Industrial use of rapeseed meal (RSM) for heating purposes is currently reported only from Hungary [22].

In the agricultural stage not only rapeseed is produced but also some 6 t/ha of straw, which has a significant impact on the overall energy balance if used as a biofuel. Straw accumulates twice as much energy as the esters, while the cake accumulates a little less energy than biodiesel. Use of biofertilisers and seed preservation technologies reduce energy consumption by 9614 MJ/ha in comparison to using mineral fertilisers and conventional drying of seeds [59]. At first sight, it might appear that the total energy consumption in the production of biodiesel can further be reduced by using exclusively renewable raw materials. However, methanol produced from the biofuel *Salix* increases the energy requirement by almost 32% [52]. The energy consumption of agricultural production of ethanol might eventually be lower than that of methanol production from fossil sources. However, methanolysis of vegetable oils is much more advantageous than ethanolysis, both from an energetic and economic point of view, as evident from Table 26 [158]. Indeed, industrial-scale production of fatty ester ethyl esters (FAEEs) is limited. Barrálcool (Barra do Bugres, MT, Brazil) operates an integrated bioethanol (sugarcane)/biodiesel (SBO, TLW) facility. Harding et al. [88] have evaluated the environmental effects of replacing methanol for ethanol. Application of FAEE generally offers larger benefits in terms of well-to-wheels energy efficiency [59] than in terms of GHG emissions. This is because methanol production is rather energy intensive, but as methanol is rich in hydrogen the greenhouse gas penalty is limited.

The area-related biodiesel yield is the highest energy amount of biodiesel that can be generated from the initial products obtained from one hectare of area under cultivation. Hectare yields can fluctuate considerably both regionally and seasonally. A restricted yield range (Table 25) was derived from long-term annual averages [108]. Conversion plants with optimal location will exceed the values obtained due to higher local yields.

Table 27
Heating values of biofuels and allocated equivalent fuels.

Fuel	Heating value (MJ/L)[a]
Rape biodiesel	32.65
Rape oil	34.59
Bioethanol	21.17
Diesel	35.87
Gasoline	32.45

After Ref. [167].

[a] Lower heating value.

The area-related final energy yield is the highest amount of bioenergy that can be generated from the products plus by-products obtainable on one hectare of area. The total energy yield is thus composed of the area-related biodiesel yield, the energetically utilisable by-products and eventually the heat and electricity provided during biodiesel generation. As by-products can be used in different ways (*e.g.* combustion and forage for rape press cake and extraction groat, energy recovery and chemical use of glycerine) allocation of an energy yield is fraught with difficulties. Moreover, by-products can be credited in different ways (based on mass, economic or energetic value). The restricted value range of rape biodiesel (Table 25) is based on heating values according to Table 27 despite the fact that glycerine is utilised preferably as a chemical base material rather than a fuel [108]. Straw can be used for fuel provision as well as for soil improvement and as a fertiliser.

6.2.2. Life cycle GHG emissions

A fundamental principle regarding the sustainability of biofuels is its potential on saving GHG emissions as compared to the substitute fossil fuels. Life cycle analyses demonstrate that most current (1st generation) biodiesel technologies deliver 40–60% life cycle GHG savings from road transport compared to that of conventional diesel if (direct or indirect) land-use change causing significant losses in carbon stocks is avoided (*cfr.* also Table 30). According to the Gallagher review estimated GHG emissions savings of rape biodiesel compared to conventional diesel range from 28% to 47% [8] (or typically 45% [7]), excluding emissions due to land-use change. The best results conform to the minimum EU sustainability criterion (35%), whereas the worst results (28%) already denote non-conformity even in the absence of land-use effects. The mean GHG output for rape biodiesel has been quoted as 43.0 g CO_2/MJ (range from −91.0 to 140.0 g CO_2 eq/MJ) as compared to 12.0 g CO_2 eq MJ for used cooking oil biodiesel (range from 10.0 to 20.2 g CO_2 eq/MJ) [21,168]. This conforms to a midrange estimate for life cycle emission savings for RME, referred to low sulphur diesel (90.3 g CO_2 eq/MJ) of 46 g CO_2 eq/MJ [169]. The range of results indicates a large heterogeneity of production conditions and significant room for improvements. The results regarding the GHG balance are strongly influenced by the energy ratio between the product and input values (as fossil energy).

GHG emissions show considerably higher uncertainty than energy efficiency values. Uncertainties in the life cycle emissions estimates for biodiesel include the allocation for co-product credits, soil carbon emissions from direct LUC and N_2O release from cultivated soil. Not unexpectedly, median-value life cycle GHG emissions decrease in case of allocation, because emissions are partitioned between co-products based on specific relationships

(*cfr.* Table 20). The substitution method, which is favoured according to the ISO 14044 standard in LCA, subtracts the credits associated with displaced products from the biodiesel chain. When land-use change is excluded from the analysis, the uncertainty in total GHG emissions derives mainly from the cultivation stage with its great variability in terms of fuel and fertiliser inputs, and uncertain parameters such as N_2O emissions from cultivated soil. Conclusions by Crutzen et al. [154] that most biofuels would not generate net GHG savings, as opposed to calculations based on IPCC emission factors, have subsequently been criticised [170]. The uncertainty in industrial conversion processes is small, both in terms of energy and GHG. Transportation activities hardly contribute to the overall GHG emission balance.

Whereas most studies have concluded that substituting diesel by biodiesel leads to lower overall GHG emissions [15,17,52, 87,171–175], a few studies [16,18] have drawn the opposite conclusion on the basis of certain assumptions. Estimates for fossil fuel-related CO_2 emissions vary considerably [18,87,88]. Zah et al. [87] have given data for the cumulative energy demand (CED) for conventional diesel (100%) and biodiesel based on European rapeseed (~60%) and American soybean (~70%) using economic allocation. It has been estimated that the combined emission of biogenic GHGs kg^{-1} BD should then not exceed 1.2 kg CO_2 eq for European rape biodiesel and 0.9 kg CO_2 eq for biodiesel from Brazilian soybeans [16]. Actually, as shown in Table 28, both biodiesel types exceed these values. If it is assumed that CED of biodiesel is only 30% of that of conventional diesel, then the values for biogenic emissions in Table 28 should not exceed 2.1 kg CO_2 eq/kg BD. Again these values are higher. The seed-to-crop stage in biodiesel production has a large impact on the life cycle emissions associated with biodiesel production from European rapeseed. Accordingly, biogenic emissions of carbonaceous GHGs and N_2O in the life cycle of European rapeseed and Brazilian soybeans, grown for up to 25 years with no tillage on arable soil for which tropical rainforest or Cerrado (savannah) was cleared, are worse than for conventional diesel. As shown above (Section 5.4), Canadian canola biodiesel with its energy efficient production system shows a much lower GHG life cycle emissions profile than European rapeseed and petrodiesel.

In principle, rape biodiesel can be produced in an environmentally friendly way, depending on the rapeseed cultivation practices without indirect land-use change effects and production technology. Tables 6, 7, 9, 11 and 23 show a breakdown by process steps of GHG emissions for biodiesel from rapeseed. Fossil fuels are used in the agricultural phase (fertilisers, pesticides, machinery), in transesterification, and for transporting the raw materials from the field to the processing plant and from there to the final users. The environmental impact from the agricultural stage (64%) is much higher than that from the fuel processing stage. Biodiesel generates lower emissions during extraction (10%) and transesterification (22%). For alcoholysis using ethanol produced from renewable resources (biomass) by bioprocesses GHG emissions are lower by about 60 kg CO_2 eq/t BD than for methanolysis, as shown by Harding et al. [88]. Overall emissions in methanolysis are higher because the current production of methanol involves solely fossil-fuel feedstocks. Transportation (3%) only plays a secondary role, even when biodiesel is produced overseas and transported with tank ships. The actual vehicle operation is CO_2-neutral as the amount of CO_2 emitted by biodiesel in the combustion phase is the same as that absorbed by the plant during its growth through photosynthesis. Biodiesel use is characterised by a small increase in NO_X compared to petrodiesel [176].

Reduced greenhouse gas emissions were determined in comparison to the corresponding fossil fuel. LCA methodology (eco-balancing) was used to derive the reduced GHG emissions (expressed in CO_2 eq, taking into account the so-called equivalence factors for CH_4, N_2O, *etc.*) developed during the combustion of fossil fuels (as energy sources) [108]. Table 25 does not consider CO_2 emissions derived from cultivation, storage, processing, conversion and combustion of the biogenic energy source. It is noticed that a biodiesel LCA for Germany reports a greenhouse gas reduction (GHGR) value of 2.0 kg CO_2 eq/L of equivalent fossil fuel [167].

GHG avoidance costs compare costs and GHG emissions of biodiesel and fossil diesel and essentially represent the costs to be raised in order to avoid a unit of GHG emissions (in CO_2 eq). Noticeably, rape oil may even show up negative CO_2 avoidance costs for its most favourable basic conditions (low provision costs, high area-related GHG reductions). Apart from GHG emissions this determines an economic advantage for the provision of rape oil as a biofuel instead of fossil diesel. As shown in Table 25, GHG avoidance costs are characterised by a very broad literature bandwidth being strongly dependent on personal and transportation costs, location and fluctuating feedstock prices.

Calculation methodologies for GHG emissions according to the EU Renewable Energy Directive [7] and US EPA [49] are different (Table 3). EU RED standardises the methodology for calculation of GHG emissions (g CO_2 eq/MJ) from production and use of biofuels (*cfr.* Table 29). Emissions from the manufacture of machinery and equivalent shall not be taken into account. In certain conditions a bonus of 29 g CO_2 eq/MJ biofuel is attributed if biomass is obtained from restored degraded land. GHG emissions (E) savings from biodiesel (BD) as compared to conventional diesel (CD) are calculated as [E(CD) - E(BD)]/E(CD). Table 30 lists typical and default values for biofuels if produced with no net carbon emissions from land-use change.

Growth of biodiesel in EU27 will be rather difficult as the GHG reduction default value for rape biodiesel is 38% (without indirect effects) (Table 30), close to the required minimum for compliance (35% in 2010) and below the limit of 50% as from 2017. Emission savings for rape biodiesel produced with no net carbon emission from land-use change need rapid improvement. In the additional

Table 28
Life cycle CO_2 equivalent emissions kg^{-1} biodiesel due to emission of carbonaceous greenhouse gases and N_2O linked to cropping.[a]

Fuel type	Emission in kg CO_2 eq/kg BD		
	Biogenic	Fossil	Total
Biodiesel from European rapeseed	2.2–3.1	2.4	4.6–5.5
Biodiesel from Brazilian soybeans ex tropical rainforest	11.2–32.5	2.7	13.9–35.2
Biodiesel from Brazilian soybeans ex Cerrado	2.7–8.0	2.7	5.4–10.7
Conventional fossil diesel	–	3.6	3.6

After Ref. [16].

[a] Allocation to vegetable oil on price basis.

Table 29
Total greenhouse gas emissions E from the production and use of biofuels.

$E = eec + el + ep + etd + eu - esca - eccs - eccr - eee$	
eec	Emissions from extraction or cultivation of raw materials.
el	Annualised emissions from carbon stock changes caused by land-use change.
ep	Emissions from processing.
etd	Emissions from transport and distribution.
eu	Emissions from the fuel in use (tailpipe emissions)[a].
esca	Emission savings from soil carbon accumulation via improved agricultural management.
eccs	Emission savings from carbon capture and geological storage.
eccr	Emission savings from carbon capture and replacement.
eee	Emission savings from excess electricity from cogeneration.

After Ref. [7].

[a] Zero for biofuels.

Table 30
Life cycle greenhouse gas emissions savings from biofuels (produced with no net carbon emissions from land-use change).

Biofuel	GHG emissions savings (%)	
	Typical value	EU default value
Rapeseed oil	58	57
Rapeseed biodiesel	45	38
Hydrotreated rape oil	51	47
Sunflower biodiesel	58	51
Soybean biodiesel	40	31
Palm oil biodiesel	36/62[a]	19/56[a]
Waste oil biodiesel	88	83
Sugarcane ethanol	71	71
Corn (maize) ethanol	56	49
Wheat straw ethanol[b]	87	85
Waste wood FT diesel[b]	95	95

After Ref. [7].

[a] Process with methane capture at oil mill.
[b] Pre-commercial *cq.* future biofuel.

EU mandate scenario (Section 6.3) compliance with the minimum limit will even be much more difficult. There is a strong drive to push cellulose or waste/residue-based biofuels instead of 1st generation biofuels. Second-generation biofuels are *supposed* to have better GHG reduction potential [177], but the impact of land-use change has been ignored.

In agriculture in temperate climates it is partly the lower crop yields (in comparison to tropical crops), partly the intensive fertiliser use and mechanical tillage of the soil that cause unfavourable environmental performance. In tropical agriculture it is primarily the clear-cutting and burning of rainforests that releases the largest quantities of CO_2, causes an increase in air pollution and has massive impacts on biodiversity. However, unlike the case of fossil fuel diesel, the environmental impacts of rape biodiesel can be reduced by various measures. Regional differences in the way energy plants are cultivated do have a relevant effect on the overall result. Changes in agricultural practices are expected to allow for larger improvements in the reduction of life cycle emissions of GHGs than industrial biodiesel production technology [178–182]. Improving agricultural practices should also be an important focus for cleaner production of rapeseed biodiesel. These may include increasing soil carbon stocks, *e.g.* by conservation tillage and return of harvest residues to arable soils [178], and improving N-efficiency by precision farming [182] and/or improved irrigation practices [181]. An optimal ratio of energetic yield and low environmental impact can also be achieved through variety and crop rotation. These improvements lower the life cycle CO_2 and N_2O emissions. However, biodiesel is far from being a cost-efficient emissions abatement strategy [15].

Conventional LCAs, which mostly focus on situations which do not require diverting the productive capacity of land from alternative uses, find that biodiesel reduces GHG emissions compared with fossil diesel. Without land-use change, European rape or soy biodiesel is estimated to generate GHG savings of about 50 g CO_2 eq/MJ (*cfr.* Table 35). Typical LCAs assign biofuels the gross benefit of using land, whereas they should only assign a net benefit. A net GHG benefit is most easily achieved by using waste carbon. Table 30 shows that cellulosic biofuels are predicted to have better GHG balances than temperate crops because of predictions of reduced growing inputs and energy needs in refining.

6.2.3. *Environmental profiles*

Whereas the accumulated non-renewable demand (CED) correlates with the GHG emissions, the situation is different for other environmental indicators. First-generation biodiesels do not offer environmental and human health benefits on all fronts. Actually, there are few biogenic energy carriers that give positive results both as regards GHG emissions and environmental LCA [87]. Used cooking oil (UCO) biodiesel is just an example. While Swiss rape biodiesel offers a GHG reduction of more than 35% as compared with the fossil reference (diesel, EURO3), there is a trade-off between minimising GHG emissions and lower total environmental impacts, as for most biofuels [87]. In particular, RME causes more emissions in the impact categories eutrophication and acidification compared with conventional diesel fuel [87,90], which is largely related to the growth of crops for biodiesel production. Environmental burdens, such as those reported in Fig. 3 [93], Fig. 5 [88] and Fig. 6 [84], which do not have a common denominator, can be expressed as one environmental index via normalisation using eco-indicators [183] or environmental impact points [110] to account for the total effects to the environment. Using such highly subjective, regionally and time specific weighing factors rape biodiesel was considered being less environmentally favourable than fossil fuel diesel in Belgium (1996) [92].

The Swiss method of ecological scarcity (UBP 06) allows for the assessment of the impacts generated by the release of pollutants and extraction of resources identified in a life cycle inventory analysis [110]. The method rates environmental impacts using an eco-points (EP) metric and permits impact assessment of life cycle inventories according to the "distance to target" principle. The ecological scarcity method weighs environmental impacts – pollutant emissions and resource consumption – by applying "eco-factors". Eco-factors, expressed as eco-points per unit of pollutant emission or resource extraction (EP or Umweltbelastungspunkt pro Mengeneinheit), are the key parameters used by the method and should be determined for the current emissions situation. It is essential to update eco-factors regularly. Life cycle assessment of biogenic fuels is required explicitly by the Swiss Mineral Oil Tax Ordinance of 1 July 2008. As shown in Table 14, various alternative impact scenarios for domestic RME production in Switzerland by replacing edible rape oil lead to higher total environmental impacts than the production and use of fossil fuels [82].

6.3. *Consequences of renewable energy action plans*

The amount of biofuels to be produced is a political decision and not determined by market trends. For instance, the US Renewable Fuels Standard (RFS2) has set a target of 36 Bgy of biofuels by 2022; a minimum GHG savings of 20% applies to conventional biofuels. The EU Renewable Energy Directive (RED)

includes a 10% energy target for the use of renewable sources (1st and 2nd generation) in road transport fuels by 2020 to be met by domestic production and imports [7]. South-east Asian countries have set their biofuel targets at similar high levels.

As biodiesel production has grown in Europe since 2000, feedstock sources have included a large expansion of domestic rapeseed production, increased imports of soy and vegetable oil and decreased oil exports. The expansion in rapeseed production has come at the expense of land devoted to wheat and some other crops, and also in use of reserve lands for biofuel production. Early EC studies concerning the 10% of transport fuel requirement by 2020 have initially ignored land-use change outside the EU assuming heavy reliance on EU set-aside lands and sourcing 30% from cellulosic ethanol by 2020 [184]. However, European set-aside lands are expected to decrease to 2–3 Mha reflecting high global agricultural demand. EU RED foresees incentives for biofuels made from wastes, residues, grasses, straw and lignocellulosic material. Second-generation biofuels are supposed to enter the market after 2015. According to another study meeting the EU target would require a land area from 20 to 30 Mha with half of its production located outside the EU [185].

According to EU RED biofuels should not be produced from raw material cultivated on land converted from high-carbon-stock or high-biodiversity areas, should comply with EU environmental sustainability criteria and should deliver a minimum level of direct GHG savings compared to fossil fuels (from at least 35% in 2009 up to 50% in 2017). Actually, it is auspicable and less discriminating that such sustainability criteria be extended beyond biofuels to all agricultural production [8]. Default values for life cycle GHG emissions from biofuels produced with no net carbon emissions from land-use change are given in Table 30. Actual values of GHG emissions can be calculated in accordance with Table 29 with the following disaggregated default values (for rape biodiesel): for cultivation (*eec*), 29; processing (*ep–eee*), 22; and transport and distribution (*etd*), 1 g CO_2 eq/MJ [7]. Table 30 shows that at present soybeans are not considered being RED compliant on the basis of the default value (31%; *cfr.* minimum legal requirement of 35%). Therefore, the soy biodiesel feedstock supplier needs to provide evidence of sustainability. Currently, still only rather few EU27 member states require sustainability certificates for biofuels and their feedstocks [22]. Without land-use effect all biofuels consumed in the EU in 2020 will meet the legal requirements of the RED threshold value of 50% direct savings compared to fossil fuel (*cfr.* Table 35).

Biodiesel production is expected to account for about 16% of total vegetable oil consumption by 2020 as compared to 10% in the 2008–2010 period. By 2020, vegetable oil use for biodiesel production will amount to 48% of EU's total domestic consumption [9]. At present, biofuels are estimated to account for about 9% of the total energy consumption in EU transport by 2020 [186]. The increased use of biofuels in the EU adds to the existing (and already increasing) demand for agricultural commodities. This increase can come from yield increases and expansion of agricultural land. It is necessary to have clear ideas about the feedstocks, production processes and land usage that will enable truly sustainable biodiesel production and avoid degradation of natural ecosystems [187]. According to RED, restrictions on the type of land that may be converted to production of biofuels feedstock crops only cover direct land-use changes (dLUC). The revised Fuel Quality Directive (FQD) includes identical sustainability criteria and targets a reduction in life cycle GHG emissions from transport fuels consumed in the EU of 6% by 2020 [12]. Developing a sustainable biofuels program requires careful consideration of unintended environmental impacts. Growth in biofuel production worldwide has severe consequences, notably indirect land-use changes (iLUC).

According to an EU working hypothesis, out of the EU mandated target of 10% renewable energy in road transport fuels by 2020 a minor part (1.4%) may be expected to come from a variety of renewable energy sources such as electricity, waste products and 2nd generation biofuels. The main portion of EU consumption (8.6%), or 27.2 Mtoe, which corresponds to an additional consumption (mandate) of 15.5 Mtoe, is then on account of 1st generation biofuels. Implementation of the EU mandate is expected to result in an increase in the relative consumption of bioethanol to biodiesel (from the energetic ratio of 17/83 in 2008 to 28/72 in 2020; *cfr.* Table 31); the bioethanol share in EU27 2009 amounted to 19.3% [47]. Yet, in absolute terms the mandate involves greater development of biodiesel (+10 Mtoe from 9.7 to 19.7 Mtoe) than bioethanol (+5.5 Mtoe from 2.0 to 7.5 Mtoe). By 2020 the EU market will represent near 25% of the total global biofuel consumption compared to 12.4% in 2008 [29]; the EU market share for biodiesel will reach 69% as compared to 52% in 2008. EU biodiesel expansion will be met by a strong growth in palm biodiesel (Table 31) even if rapeseed remains the most used feedstock in absolute terms. Soy biodiesel will shrink as a result of EU import restrictions on US biodiesel since 2009 and the relative price increase of soybeans driven by Asian growth.

Recently, (rape) biodiesel production in the EU has been consolidating showing only restrained growth. As shown in Table 32, the EU additional mandate will lead to an increase of 37% in the global production share of biodiesel and an increase of 33% for rape biodiesel. Yet, the market shares for biodiesels remain much lower than that of bioethanol. Rapeseed oil remains the main biodiesel feedstock at the global level, followed by palm and soybean oil.

Table 33 illustrates the shift in the EU production structure. Overall, EU biofuel production will increase from 10.1 Mtoe in 2008 to 17.8/20.9 Mtoe (with/without trade liberalisation) in 2020. For biodiesel, the share of processed rapeseed oil in the biodiesel sector falls from 78% to 64% under the competition of palm oil (from 10% to 19%). With full trade liberalisation, biodiesel will represent 92.5% of total EU biofuel production.

The future biofuels demand requires more energy crops. The balance sheet of Table 34 shows the global consequences of the incremental EU demand for oilseed crops. The extent to which the additional demand for biofuels (as well as for food and feed) will

Table 31
EU consumption pattern by biofuel feedstock, percent.

Feedstock	2008	2020
Palm oil	4	9
Rapeseed oil	57	51
Soybean oil	20	9
Sunflower oil	2	3
All biodiesel	83	72
All bioethanol	17	28

After Ref. [29].

Table 32
World production of biofuels by feedstock,[a] percent.

Biofuel	2008	2020
Rapeseed	4.55	6.03
Palm fruit	2.66	4.15
Soybean	2.83	3.45
Sunflower	0.95	1.31
Biodiesel	10.99	14.94
Bioethanol	89.01	85.06

After Ref. [29].

[a] Energy content.

Table 33
EU biofuel production by feedstock,[a] percent.

Feedstock	2008	2020[b]
Rapeseed	62.04	44.37/59.58
Palm fruit	7.55	12.87/16.96
Soybean	6.52	7.45/9.90
Sunflower	3.17	4.56/6.09
Biodiesel	79.29	69.25/92.54
Bioethanol	20.71	30.75/7.46

After Ref. [29].

[a] Energy content.
[b] No trade liberalisation/trade liberalisation.

Table 34
Global consequences of the incremental EU demand for oilcrops (kt).[a]

Oilseed	Biodiesel demand	Additional supply	Total demand displacement
Rapeseed	4456.9	2474.4	−1982.5
Palm	3850.6	5342.0	1491.4
Soybean	2063.5	1270.8	−792.8
Sunflower	933.3	1172.4	239.1

After Ref. [29].

[a] No trade liberalisation scenario.

be met by an increase in supply (*e.g.* land reallocation) depends on the feedstock crop. Almost 60% of the biofuel demand is met by new production. The remaining oil is displaced from other sources of demand. In some cases, this additional demand may not be matched by an additional supply. For rapeseed and soybean oil the additional demand is only partially matched by additional supply; for rapeseed the replacement ratio between additional supply and demand is 78%, for soybean oil only 40%. Displaced rapeseed oil is replaced by all the other types of vegetable oils. Additional production of palm oil, and to a lesser extent, sunflower oil is larger than the demand in their respective biodiesel sectors. Their increased production also replaces rapeseed and soybean oils used for biodiesel production and not provided for by additional productions of these oilcrops. Overall only 10% of total vegetable oils is not replaced. A reallocation of production will result. The greatest concern with the rapid expansion of vegetable oils is with palm and soybean oil. Rapeseed expansion is considered being less problematic when confined to Europe where there is greater environmental control. However, increases in RME production are impeded by the restricted acreage of cultivable areas and by the implications of international trade agreements, limiting the substitution of imported soybean meal by rapeseed meal. The livestock sector plays a critical role in the biofuel dynamics.

According to the European *Biomass Action Plan* [188] the 5.75% energy target by 2010 required about 17 Mha of cultivated land, or about 20% of the European tillable land. This (modest) biofuels target could not be met by domestically produced feedstock only. Future increased EU biofuel consumption will have to rely even more heavily on imports of feedstocks than on domestic sources because of land-use constraints and high costs [189]. Increasing consumption of domestically produced RSO for biodiesel uses is expected to lead to a considerably gap in the (increasing) EU food oil demand, resulting in increased imports of rapeseed (*e.g.* from CIS countries and India) and of other vegetable oils (notably palm oil) [27]. Main sources for EU27 rapeseed oil imports in 2009/2010 were UAE, Russia and Belarus [22].

The trade consequences of the additional mandate scenario for the EU are as follows: biodiesel imports will triple from 0.8 Mtoe in 2008 to 2.6 Mtoe in 2020. In terms of feedstock effects, imports of rapeseed will increase drastically (+ 6.2 Mtoe). The imports of rapeseed oil, palm oil, and soybean (both oil and beans) and sunflower oil also increase, although to a lesser extent than rapeseed imports (totalling 4.7 Mtoe). Under trade liberalisation, the EU can grow more rapeseed, at the expense of sugar beet and cereals. Due to the strong biodiesel component in the mandate an increase in price for oilseed crops is forecasted. EU biofuels policy causes relative prices to change and relocates production.

Out of about 13,418 Mha global land-use areas in year 2000 some 1534 Mha are devoted to agricultural crops [190]. Land used to produce the feedstocks from the current 1st generation biofuels is about 2% of the crop area or about 27 Mha but bound to increase dramatically in view of the rapidly growing demand for biomass energy. There is general consensus that large amounts of land will be needed to produce biofuels by 2050 if aggressive biofuels plans are adopted globally, that tropical regions are important locations for growing biofuel feedstocks, and that pasture lands (broadly defined) will be a major source of lands used for biofuels [191]. In developed countries the area expansion is limited and the production increase is only caused by yield increase. However, growth rates of yields have gradually slowed during the last two decades. Regions where large areas of land are potentially available for biomass production are in particular North and South America, Central Africa and Oceania.

The EU *Strategy for Biofuels* [192] indicates that Europe promotes production of raw material for biofuels in extra-European countries, although this determines another high degree of energy dependency. Energy independency is a declared objective of the EU to stimulate biodiesel production. Europe shifts the environmental burden of energy farming (pollution, soil erosion, reduction of wild and agricultural biodiversity, decrease in water resources and quality, deforestation) to outside the EU, in particular to natural habitats of global importance such as the Brazilian Cerrado and IndoMalay rainforests [193]. As to the impact on ecosystems, large-scale feedstock production could well lead to habitat and biodiversity losses [194]. Vegetable oil is a commodity that is associated with these problems.

Large-scale production of biofuels (accounting for over 15% of total commercial energy requirement) is constrained both socio-economically and biophysically. In particular, the energy throughput per unit of labour ($<$ 250 MJ/h) is far below that achievable by the fossil energy sector (about 10,000 MJ/h) [14]. Obvious fundamental biophysical constraints on biodiesel production are that the soils and rainfall must support healthy production.

6.3.1. *Land-use effects*

Additional feedstock production affects land-use. During the 2008–2020 period significant land-use changes, *i.e.* area(s) transformed (land type and geographical location) as a result of crop consumption in a given region, will take place driven by additional food demand and non-food use. The question how an expanding bioenergy sector will interact with other land uses, such as food production, biodiversity, soil and nature conservation, and carbon sequestration, has been analysed insufficiently. Close attention needs to be paid to the economics of scarce land resources and the competition for land between food and energy crop production under stringest CO_2 carbon policies. A framework for LCI modelling of land-use changes induced by crop consumption has been proposed [70].

Land-use change (LUC) is the most controversial and uncertain issue associated with biofuels [195]. Direct LUC (dLUC) occurs if previously uncultivated land is used to produce biomass feedstocks. Typical dLUC scenarios are improved grassland, and low- or full-tillage cropland converted to rapeseed cultivation. Indirect LUC (iLUC) is associated with the displacement of an existing

agricultural activity. The critical questions revolve around indirect land-use. Distinction between direct and indirect uses of land for biofuels is usually economically meaningless. Land-use consequences of demand for a particular biodiesel feedstock generally depend on where that feedstock is produced most economically. Some LCA studies examined provide insights in how the expanding bioenergy sector interacts with other land uses (food/feed) [64,82]. The environmental impacts of local supply (rapeseed) *vs.* global supply of vegetable oil (palm oil) to the European market have been evaluated. Socio-economic consequences were also assessed (for Italy) [11].

Production of a specific crop may be enhanced by displacement of other crops (to be compensated for by production elsewhere), expansion of croplands or intensification of existing production [70]. Displacement is constrained by climate conditions, soil properties and crop rotation schemes. Displacement embodies the fuel *vs.* food/feed controversy. As demand for agricultural commodities is growing, part of that additional demand will be met through an increase in world arable land (presently *ca.* 1500 Mha cropland). Overall exploited land is forecasted to increase by 0.25–1.4%. Expansion of croplands – with high marginal costs – typically takes place at the expense of nature, but may also occur on land already transformed. Agricultural opportunities in highly populated areas (as in many European countries) are restricted. This sets a limit to domestic growth. By diversifying crop rotations, the EU27 oilseeds area is expected to increase from 12 Mha in 2010 to 13.5 Mha by 2020. The additional EU biofuels mandate requires from 1.4 Mha [29] to 5.2 Mha [189]. The EU does not have enough arable capacity on existing arable land area and set-asides to reach the 2020 biofuels target without increasing food imports. Actually, the global agricultural land-use of the EU already exceeds the domestic agricultural land by nearly 20% [187]. In recent years, croplands in Europe and USA have even been contracting by 1.7% and 1.1%, respectively. On the other hand, other areas (Argentina, Brazil, Canada and USA) are without much agricultural restrictions. The greatest cropland extensions are expected to occur in Sub Saharan Africa (SSA) (+18%), Brazil (+11%) and Central America (+7%), and South East Asia (+7%) [196]. Deforestation occurs mainly in South East Asia (–18% of primary forest) and Brazil (–10%). A large proportion of LUC in the biodiesel scenario is also due to expansion of rapeseed outside the EU, particularly in India.

Increases in cropping intensity and yield growth per hectare (intensification) reduce the need for cropland expansion. Intensification can be achieved through optimisation (application of fertilisers, pesticides and irrigation) or technological development (improved mechanical aids, agricultural practices and higher yielding crop strains). Optimisation of production is subject to diminishing returns: the higher the level of fertiliser, pesticide or irrigation, the lower the yield increase per unit of input (situation in developed countries). There exists an optimal level. Moreover, legal fertiliser and pesticide restrictions may apply such as a limit on organic N fertilisation of 170 kg/ha/yr in many EU countries [41]. The environmental consequences of increased domestic production of RME in Switzerland with displacement of edible rape oil (and imports of other vegetable oils) or feed barley have been evaluated [82]. Only increased agricultural production by intensification leads to lower GHG emissions *and* lower overall environmental impacts than the fossil reference.

The European Union (EU) recognises that various uncertainties associated with indirect land-use change (iLUC) modelling remain to be addressed, which could significantly impact the results of biodiesel life-cycle studies [197]. Consequences of total land-use change – direct and indirect – of the European biofuels policy have been assessed for a mandate leading to an increase in global cropland area of almost 1.8 Mha [29]. The most affected regions in terms of cropland extension are considered being Latin America (in particular Brazil), CIS and SSA. Sources of extension of cropland worldwide are pasture (42.8%), managed forest (37.4%), followed by savannah and grassland, including the Brazilian Cerrado (16.4%), and finally primary forest (3.4%), *i.e.* almost 80% within managed land (pasture and managed forest) [29]. The Gallagher review to RFA [8] suggests that no future bioenergy crops should be cultivated on agricultural land since this may displace food crops to pristine environments where other ecosystems could be threatened. Idle or marginal lands should be used instead. Residues from agriculture and forestry, together with those from the human food chain, offer the only source of bioenergy that does not require land-use change additional to that required for food production itself.

With increasing demands for biofuel feedstocks it is important to know how much of this demand is met by additional production and how much is displaced by other uses. Expectations are more than 80% of increased production of key oilseeds and sugar crops will come from extensification (additional land) rather than from intensification (higher yields). For rapeseed in the EU this figure is even 90%. Within the EU, cropland extension on account of the mandate remains below 6% of global value, representing less than 0.15% of EU cropland. The increase in demand for biodiesel leads to an extension of the land area needed for oilseed production at the expense of land for bioethanol feedstocks and other crops. Within the EU, the land area increases mainly for the production of rapeseed (+870 kha) and, to a lower extent, sunflower (+220 kha). Rapeseed production displaces EU cereals (wheat, corn), other oilseeds and vegetable fruits. Without trade liberalisation, the extension of oilseeds (rapeseed, sunflower) and the relocation of cereals production dominate the global pattern, leading to the concentration of most land-use changes in CIS countries (*e.g.* Ukraine). Under the trade liberalisation scenario, Brazil experiences the highest increase in terms of cropland. The effects of 2nd generation biofuels on land-use changes are currently unknown and need further modelling. It is not unreasonable to suppose that the problem of land scarcity will be alleviated by future biomass-based technologies which make use of the entire plant instead of only the oil-rich parts of oilcrops.

The land requirement for biodiesel production varies considerably for different oilseeds due to different crop yields and oil content. Typical best values for oilseed rape are 1150–1200 L biodiesel/ha [198,199]. Assumptions about land availability and fertility and rapeseed yields are central to the total rape biodiesel potential. The vast differences in yields between different types of land make an estimate of the additional arable land needed to reach the Biofuels Directive target difficult. Ecofys quoted a 4.9 Mha of land-use change extra-EU to meet a 7% energy target [200]. Typical yields of expanded (usually less fertile) land are below average. The supply increase for rapeseed is expected to be driven mainly by land-use (91% EU; 86% world) and only marginally by yield increase through fertilisers (1% EU; 6% world). Even without changing the amount of fertiliser per hectare, technological progress leads to higher production per hectare and to less fertiliser by unit of production. However, the consequences on direct savings are limited and of the order of 0.03 g CO_2 eq/MJ for soybean (a crop with low N fertiliser intensity) and 0.28 g CO_2 eq/MJ for rapeseed.

Agricultural products are subject to international trade, and consequently, the geographical scope is global. While feedstock (or biodiesel) can be imported into the EU, this will raise costs and contribute to transport energy consumption and emissions. Transportation and trade costs might make intensification more attractive than imports in regions without possibilities for cropland expansion (EU). Higher yields help to reduce the amount of land required to cope with additional crop demand. Globally,

production is shifting from developed countries (with high input levels) to emerging countries using less intensive techniques and reduced average use of fertilisers. In conditions of initial lower fertiliser use rates, more intensification can be achieved through additional fertiliser (up to 20% for rapeseed). The intensification potential for the traditional rapeseed crop is quite low in the EU, where much effort has already been devoted to plant breeding and cultivation method development, and is not expected to lead to considerable yield increases. Table 1 shows yield projections for rapeseed by 2020. For rapeseed the average yield for new production is 3.35 t/ha.

6.3.2. Land emissions

Serious concerns have been expressed about the negative environmental impacts of the unintended consequences of biofuel production, particularly the indirect land-use change (iLUC) impact of releasing more carbon emissions as forests and pristine lands are converted to cropland due to biofuel expansion. One of the problems is that iLUC is a phenomenon that is impossible to directly observe or measure. Consequently, estimated land-use change can never be validated. Although the scale of effects of iLUC is uncertain the effect can potentially lead to a significant net increase in emissions and reduces or even totally eliminates the GHG benefits of biodiesel. Quantification of GHG emissions from land-use change requires knowledge on the type of crop that has been displaced, the type of land-use change that occurs as a consequence of the displaced crop, and the amount of carbon released arising from land-use change. GHG emissions from LUC change vary widely between specific location and biomass and stem both from above ground carbon (in forests, savannahs and wetlands) and below ground carbon (in soil and roots of temperate grasslands). Different LUC scenarios strongly affect the average and uncertainty range of total GHG emissions for biodiesel even more than for bioethanol [47]. IPCC provides some guidance on the estimation of direct impacts (*e.g.* the conversion of forest or grassland to annual or perennial biofuel crops) based on climate zone, ecological zone or soil type [201].

The prospects of large-scale biodiesel production requires extensive modelling of the interactions between bioenergy, food and materials production (competition for resources), biodiversity, soil and nature conservation. Various EU-initiated studies have evaluated the environmental consequences of global land-use change as a result of the realisation of the renewed 2020 biofuel targets in terms of GHG emissions [29,186,189,202–206]. iLUC impacts depend strongly on base assumptions in modelling, including yields, food/feed consumption, land classification, carbon stock values, and geographical origin of the feedstock. Different assumptions have been made as to the total share of biofuels for road transport by 2020 (up to 8.6% in energy), the amount of advanced biofuels (up to 1.5%), as well as the biodiesel/bioethanol ratio (from 83/17 to 55/45). The latter ratio strongly affects the iLUC impact with average emissions of 18 and 45 g CO_2 eq/MJ for ratios of 55/45 and 75/25, respectively, in a scenario of 5.6% conventional and 1.5% advanced biofuels [186]. These values, which are to be summed to the crop-specific GHG emissions for rapeseed of about 44 g CO_2 eq/MJ, denote the clear inferiority of biodiesel – whether generated in EU or USA – as compared to sugarcane ethanol in terms of environmental impacts. Sugarcane also has a high energetic efficiency ($\sim$ 8:1). An increase in biofuels consumption in the EU of 17.8 Mtoe was prospected (mostly from EU27 domestic biodiesel and import of bioethanol from Brazil) [204]. iLUC emission coefficients increase with the size of the EU mandate and rapidly erode the environmental sustainability of biofuels. Of overriding importance in the GHG emission estimates is the proportion of forest converted to cropland with estimates ranging from 5% to 36%, as well as the impact of peatland. There is also little consensus on the attribution of total cropland area subject to indirect land-use change for 2020; estimates range from 242 to 1928 kha/Mtoe of biodiesel [186]. Most of the EU modelled scenarios project that the largest share of LUC for biodiesel will occur outside the EU. Edwards et al. compared iLUC results produced by different economic models for marginal increases (1 Mtoe) in biofuel production from different feedstocks [203].

Laborde has assessed land-use change consequences of the European biofuels policy for various trade scenarios assuming consumption of 27.2 Mtoe 1st generation biofuels (biodiesel/bioethanol in 72/28 ratio) by 2020 (or 86% of target), which requires a 15.5 Mtoe additional mandate [29]. The 1.8 Mha LUC would take place mainly within managed land (80%) with one-third of total emissions on account of peat soil (at 55 t CO_2 eq/ha/yr). Peatlands are high-risk emission locations. Land emissions over a 20 year period, induced by the additional EU biofuels mandate, are about 39.1 g CO_2 eq/MJ biofuel for full mandate but even still 34.5 g CO_2 eq/MJ for half mandate, denoting non-linearity. Total amount of emissions is about 500 Mt CO_2. There are large differences between the LUC effects of biodiesel feedstock and ethanol crops. LUC emission coefficients at the mandate level are on average 54.3 g CO_2 eq/MJ for biodiesel feedstocks and 11.1 g CO_2 eq/MJ for bioethanol feedstocks. Differences in LUC emissions for oilseeds are small (Table 35). Among vegetable oils sunflower appears to be the best feedstock in terms of LUC emissions whereas soybean shows the highest emission coefficient. Rapeseed is close to oilseed average (54.2 g CO_2 eq/MJ). Rapeseed LUC emissions are reduced by only 8% if the additional EU mandate is halved [29]. For another alternative scenario, namely a biodiesel/bioethanol ratio of 55/45 and a 5.6% mandate instead of 8.7%, an average LUC emission coefficient for biofuels of 17 g CO_2 eq/MJ was derived (peatland emissions not included) [204].

As shown in Table 35, with improved technology and yields all biofuels qualify for the EU sustainability scheme that requires direct savings of at least 45 g CO_2 eq/MJ or 50% of fossil fuel emissions. On the basis of improved 2020 technology (*i.e.* new plants) with annual direct savings of 57 g CO_2 eq/MJ (20 years) and annual LUC emissions of 38 g CO_2/MJ net emission savings of 19 g CO_2 eq/MJ of biofuel consumption are calculated for the additional EU mandate (no change in trade regime). In other words, land-use change emissions prevail over direct emissions of methane and nitrous oxide from agricultural systems and cancel

Table 35
Estimated biodiesel emissions and savings (g CO_2 eq/MJ) in 2020 for additional EU mandate.[a]

Biofuel	Direct savings[b]	LUC emissions[c]	Net savings[c]
Rapeseed	50	54(67)	−4(−17)
Sunflower	58	52(61)	6(−3)
Soybean	45	56(71)	−11(−26)
Palm fruit[f]	58	54(85)	4(−27)
Biodiesel/bioethanol[d]	57	38(50)	19(7)
	In percentage of GHG savings[e]		
Rapeseed	55	60	−5
Sunflower	64	58	6
Soybean	50	62	−12
Palm fruit[f]	64	60	4
Biodiesel/bioethanol[d]	63	42	21

After Refs. [29, 206].

[a] For trade policy status quo.
[b] Based on improved technology and yields in 2020.
[c] In parenthesis effects of added revised peat emissions [207].
[d] Biodiesel/bioethanol ratio 72/28.
[e] With a 90.3 g CO_2 eq/MJ reference for fossil fuel.
[f] Methane capture at mill technology.

almost two-thirds of the total direct emission savings for the entire EU biofuels mandate. The emission savings of shifting from fossil fuels to renewable biofuels are even totally annihilated by LUC emissions for most biodiesel feedstocks (Table 35). The overall mandate will thus not achieve the intended saving of over 50% compared to fossil fuels.

Biodiesel crops generate very low net emissions savings or even positive emissions by MJ of biofuel. Among biodiesel feedstocks, only the most costly vegetable oil (sunflower) and most competitive oil (palm oil) generate small net emission savings (6 and 4 g CO_2 eq/MJ, respectively), less than 6% of the fossil fuel comparator. For palm oil it is a requirement that all the additional production is manufactured in installations equipped with methane capture facilities. For rapeseed, in order to achieve net emission savings it is crucial that biodiesel processing technology is improved and that direct savings increase. For instance, with a 66% direct savings (60 g CO_2 eq/MJ) the rape biodiesel pathway may contribute to emissions reduction (*cfr.* Table 35). As intensification of production per unit of land area is not expected to lead to a large yield increase, only more extensive land-use is the main source of increased supply. Net emissions reduction over 20 years is only achieved by ethanol crops, and at a much lower level by sunflower and palm oil for biodiesel.

The most important sources of CO_2 emissions are peatlands (34%), managed forest (31%), carbon in mineral soil (30%) and primary forest (5%), given the share of biodiesel and vegetable oils in the EU biofuels market. Peatland is associated with palm oil production in tropical countries where it plays a critical role and contributes up to 70% of crop specific LUC emissions in palm oil production. About 30% of palm plantation expansion in South East Asia takes place on peats, which are strong GHG emitters [203]. As all vegetable oil markets are strongly integrated, palm oil plays an important role as a biodiesel feedstock (as well as for hydrodiesel) in the EU and in the IndoMalay region and/or as a replacement for vegetable oils displaced from other uses. Although some vegetable oils are not replaced by their own kind, they are replaced by other vegetable oils, thus not leading to true savings on emissions. The breakdown of crop specific annual carbon release for rapeseed from various sources is as follows: forest biomass, 22; carbon mineral soils 17; and palm extension on peat lands, 15 g CO_2 eq/MJ.

Malins has reported the most recent update of modelling of iLUC emissions from the additional EU biofuels mandate (biodiesel/bioethanol 72/28) [206]. About 41% of the modelled mandate was attributed to rapeseed with the additional vegetable oil demand for rapeseed being met for 78.2% by rapeseed oil supply and for 21.8% by palm oil/other oils. In view of the reported high peat oxidations from the IndoMalay region (from 19 to 115 t CO_2 eq/ha/yr) a more realistic estimate for the carbon emissions from degraded peatland under palm cultivation (annualised over 20 years) was used (106 t CO_2/ha/yr [207] instead of the previously used underestimate of 55 t CO_2/ha/yr [203]). This raises the carbon intensity for biofuels in the EU mandate by another 12 g CO_2 eq/MJ from 38 to 50 g CO_2 eq/MJ on average, thus further increasing the net emissions reported in Table 35. This greatly reduces the prospects for the EU biofuels mandate to deliver net climate change mitigation benefits. More specifically, the carbon intensity of large-scale production of rapeseed increases by 12 g CO_2 eq/MJ to a total of 106 g CO_2 eq/MJ. With the added iLUC from peat emissions sunflower oil is the best and palm oil the worst biodiesel feedstock for total biodiesel emissions [206]. With the revised peat emissions biofuels (biodiesel/bioethanol) to meet the mandate would have an average carbon intensity (CI) of about 87.5 g CO_2 eq/MJ, higher than the fossil fuel comparator from the RED (83.8 g CO_2 eq/MJ). All biodiesels are considerably worse (*cfr.* Table 35). Biodiesel from rapeseed, soybean and palm oil have negative GHG savings when added iLUC is included, with sunflower being almost neutral. Only bioethanol has the potential to deliver savings of over 50%. An important constraint for biodiesel production as compared to bioethanol is its considerably greater need for land-use. With the overwhelming effect of land-use changes it is doubtful that technological improvements for biodiesel production will ever be able to compensate the net emissions losses.

Various other approaches have been reported for estimating potential GHG impacts from indirect land-use change: partial equilibrium modelling [1] and the use of iLUC factors [208]. Also the iLUC factor approach suggests no net savings for rape biodiesel. Although the EU Renewable Energy Directive contains proposals to restrict the conversion of certain land types for biofuel feedstock this has not been extended to restrict indirect land-use change.

GHG emissions caused by indirect land-use changes should be minimised. When land for feedstock production is expanded in pristine environments (or even managed forest/pasture) it would have different consequences for different regions depending on their carbon stocks. The GHG emission criterion implies that direct use of carbon-rich lands is generally inappropriate for biodiesel. Different feedstocks will have different implications for different regions. Emissions from set-aside land put in production reduce by approximately half the savings of oilseed rape biodiesel compared to feedstock grown on existing agricultural land. GHG savings are better where biocrops are grown on rotational rather than permanent set-aside or fallow land [8]. Avoiding excessive tillage can also preserve soil carbon. Where feedstock production requires the dedicated use of land, a significant net gain in GHG emissions is likely only if the land is otherwise marginal from a carbon perspective. This means it neither sequesters significant storage nor produces significant food, yet it produces biofuel feedstocks abundantly. This typically implies land wet enough to support high plant growth but degraded and unproductive for other reasons. For lands with a low soil carbon content (*e.g.* which has been in use recently or has not been fallow for very long) good net GHG savings and relatively short payback periods are possible. Use of degraded grasslands or marginal lands for energy crop production could avoid impacts related to LUC and reduce GHG emissions [31]. It has been estimated that the human food market increases the LUC effect by 15–20% for most oilseeds [29].

6.3.3. Biofuel policy issues

Biofuels policy is the most significant demand driver for rapeseed; biofuels use accounts for about two thirds of total EU27 rapeseed oil consumption 2011/2012 [22].

Uncertainty regarding cropland extension in the EU is very limited. EU capacity to intensify crop production (yield increase) or to free pasture land (livestock intensification) is limited overall. The only crop for which EU cropland extension is a source of significant uncertainty is rapeseed. At the world level, however, uncertainties are much stronger. Most of the uncertainty affecting the LUC effects of the EU biofuels policy concern the rest of the world. This leaves little control to EU policymakers.

The LUC effect cancels the environmental benefit of the EU biodiesel policy. This calls for a mitigation strategy. In all fairness, however, it should be considered that biodiesel production-related emissions are no more adverse than those generated by other agricultural productions, but they are additional. Ethanol carries considerable lower risk of land-use emissions than biodiesel. This implies that the EU should benefit from a more equilibrated bioethanol/biodiesel ratio.

The biofuel policies increase the price of energy contents in crops (oils and sugar) but lead to a relative reduction of the price of proteins (meal). The policy provides a premium to oils and fats. The biofuels policy causes the relative prices to change and therefore reallocates production.

Large-scale use of biofuels and in particular biodiesel is increasingly being questioned. Many of the attributed benefits of biofuels are being re-examined. Production of almost 7.2 EJ of biofuels by 2020 would require almost 83 Mha (yielding on average 86 GJ/ha). Production of biodiesel from oilseeds is less favourable as 25 Mha are needed to produce just 0.75 EJ of biodiesel [187]. The International Energy Agency is particularly sceptic regarding the future of 1st generation biofuels such as rape biodiesel which can contribute to pressures on food supplies and have a relatively low potential for the reduction of GHG emissions. Biodiesel from oilseeds is expected to be phased out by 2050.

7. Optimised rape biodiesel

Apart from sustainability requirements, future rape biodiesel also needs to meet several new property demands to ensure its usability in the long term as a neat biodiesel for trucks or as a blend in passenger cars [209]. Rapeseed methyl ester (RME) is currently not compatible with diesel particulate filters and releases for B100 have been withdrawn. Moreover, at present RME may also not be considered as an optimal prospective fuel in view of its sharp boiling curve which is less beneficial for good fuel ignition and combustion in the cylinder. The boiling characteristics of RME probably limit its further usability in high-tech engines complying with the forthcoming Euro VI exhaust gas regulations in 2014. The boiling line needs to be adapted to future engines with lower compression ratios and a more homogeneous fuel-air charging. It is important to lower the boiling curve by higher shorter chain length (C12–C16) levels, without compromising the oxidative stability. Redesign of the ideal fatty acid profile requires plant breeding but blending with palm kernel or coconut methyl esters should also be considered, certainly at short term. Also the phosphorus and metal contents of future biodiesels are likely to become significantly lower than the present specification limits according to EN 14214. This requires improvements in transesterification processing. Finally, RME also faces competition from hydrogenated vegetable oil (HVO), which has several chemical and physical advantages. In Germany, blending fuel with almost 7% biodiesel and 3% HVO is foreseen [210]. Improvement of RME is urgently needed.

8. Conclusions

On balance, general conclusions drawn from rape biodiesel LCAs are as follows. A basic factor in the use of energy crops is the application of rational techniques. Techniques can contribute to reducing inputs and increasing outputs. However, in most situations, inputs (machinery, fertilisers) cannot be decreased beyond certain limits. The balance then depends on outputs. When energy gain and ratio are low a crop is not valid as an energy crop, but should find other use (food or feed).

Biodiesel is a niche fuel with its production capacity being limited by land area constraints, not by energy input. Biodiesel production needs to be sustainable. The fossil energy and GHG savings of conventionally produced biodiesel are critically dependent on cultivation/manufacturing processes and the allocation of by-products. LCAs of country-specific and feedstock-specific biodiesel pathways assist in suggesting improvements in specific biodiesel pathways in order to comply with international sustainability criteria. More sustainable production of biodiesel requires above all improving agricultural practices. These may include reduction of soil erosion and increase in soil carbon stocks, *e.g.* by conservation tillage, return of harvest residues and improving N-efficiency by precision agriculture and/or improved irrigation practices. High yielding legumes should be integrated into crop rotation. The environmental impact of RME production can further be diminished by use of higher yield rapeseed species, better fertiliser management (increased organic fertiliser), application of less toxic herbicides, improved drying, crushing and oil extraction practices, and use of fuel-efficient agricultural machinery. Advanced seed preservation technology reduces the total energy consumption [59]. Biotechnology offers opportunities for reducing environmental impacts. Nitrogen Use Efficiency (NUE) canola is a recent development.

The use of RME instead of fossil diesel fuel produces environmental advantages as well as disadvantages. Produced in limited quantities RME is beneficial with respect to energy conservation and reduces the greenhouse effect but is detrimental regarding acidification, nutrification of soils and surface water and ozone depletion, and indifferent for the impact category photo smog. In scenarios of high biodiesel mandate rapeseed specific LCA results are overshadowed by crop iLUC effects. Biodiesel may have considerably higher GHG emissions than petrodiesel if the most severe land-use change scenario (peatland converted to biocrop cultivation) is considered. In view of the overwhelming impact of iLUC contributions to the total GHG emissions legally imposed environmental sustainability targets can only be met by minimising land-use impacts (2nd generation biofuels) or by considerable reduction of *direct* emissions; for the latter, this survey has identified many options in the agricultural stage. Rapeseed may only achieve net emission savings if its processing technology is improved and direct savings as compared to fossil fuel increased. There is an urgent need for new technology that is more energy efficient and improves the overall life cycle analysis of biodiesel production. Technological improvements range from new catalysts (heterogeneous, lipase) to process intensification, alternative reactor concepts and separation technologies, but all is work-in-progress and comes at a price [160,211,212]. GHG emission reductions always entail costs [152] and higher costs of biofuels impair their profitability. Large part of the present excess biodiesel nameplate capacity risks staying idle forever.

Biofuels should be promoted in a manner that encourages greater agricultural productivity and the use of degraded land. Additional land-use and biomass production for non-food purposes will have to be most efficient. Without further action the current European biofuels policies do not deliver any net GHG benefits. Corrective action may consist in modifying the minimum GHG emissions saving. The renewable energy mandate should be revised downward. A mitigation strategy for European biodiesel is necessary, as already set out in the Gallagher review [8]. The clear hierarchy between bioethanol and biodiesel in terms of LUC emissions calls for a larger share of bioethanol in biofuels policies, in particular in Europe. Sugar beet/cane alcohol is economically a more efficient product than biodiesel and leads to higher emission savings. Measures to shift the demand from biodiesel to bioethanol have already been recommended [206]. This could be achieved by raising the *direct* GHG savings threshold.

In terms of land-use (and consequent agrochemicals applications) rapeseed and soybean cultivation is to be preferred over sunflower for biodiesel production [83], although this is not true if large-scale GHG emissions due to land-use change are considered. Anyway, the potential of domestic European bioenergy based on rape biodiesel is limited. Expanding agricultural energy production may lead to land-use conflicts with other land uses such as food production or the conservation of natural areas. For crops harvested from land already in production life cycle GHG emissions of rape biodiesel are 45% of those of diesel fuel. Converting intact ecosystems to production would result in reduced GHG savings or even net GHG release from biodiesel production. However, extensivation not always incurs in disturbing carbon sinks such as peatlands and tropical forests. Rape biodiesel would provide

greater benefits if its biomass feedstock were produced with lower agricultural input (*i.e.* less energy, fertilisers, and pesticides) on land with low agricultural value, and requires low-input energy to convert feedstock to biofuel. Any solution to improve biofuel yield without more emissions (*e.g.* no additional fertilisers) is welcome. However, this is unlikely to deliver positive effects on land-use already by 2020. Use of improved agricultural practices aiming at reducing emissions, *e.g.* low tillage, may deliver quick improvements. Using low-carbon agricultural practices and technologies to increase yield (*e.g.* biotech) could mitigate the emissions linked to land-use changes by reducing the requirement of additional land. Existing EU biotechnology regulations need to be challenged. The real challenge, however, lies in implementation of low-carbon agriculture in the coming decades with good governance of scarce land resources, *i.e.* sustainable agriculture at the global level. Local expansions of cultivated area on set-aside land are preferable to displacement of crops which are compensated for by increased agricultural production abroad [64]. International monitoring capacities for land-use practices need to be improved.

The limit of sustainable production of rapeseed biodiesel is within sight. Biodiesel presents a scale-up problem both in terms of land area requirement and in the allocation of the energy inputs to co-products. Allocations applied for small-scale production (as assumed in most LCAs), where the by-products can replace other similar products, do almost certainly not apply on a very large scale. Sustainable long-term production of rape biodiesel requires complementary socio-economic assessment. Based on this review, it is not possible to establish whether a large-scale rapeseed supply for energy is an attractive option for climate change mitigation in the energy sector in the long run. First, there is insufficient insight in how the expanding biodiesel sector will interact with other land uses. Moreover, the socio-economic consequences of a global large-scale expansion of biomass use for energy are still obscure [213]. Future studies should thus not assess the prospects for (rape) biodiesel in isolation, but instead adopt a broader approach where several land-use based mitigation options are considered as well as socio-economic goals. However, biodiesel at large is not a cost-effective GHG emissions abatement strategy [15] and also the energy throughput per unit of labour of biodiesel (*cfr.* Table 2) is far from satisfactory [14].

Some additional problems lie ahead of rape biodiesel. RME is currently not suitable for diesel particulate filters [209]. Moreover, the boiling characteristic of RME is a problem that presumably limits its further usability in Euro VI engines (2014). Its fatty acid profile requires optimisation. The phosphorus and metal contents of future biodiesel must become significantly lower than the actual specification limits.

Supply of land is tight and areas of land left for beneficial environmental use for biofuels are necessarily restrictive [191]. New croplands can be developed in the tropics, where biodiversity values are high. Rates of deforestation in parts of South America, Africa and South-East Asia should be slowed down and halted. From an environmental standpoint, there are few areas where biofuels are an acceptable use of land given the alternative uses. Advances in high-yield agriculture reduce the need to convert forests to farmland [112]. As suitable areas for biofuel production are likely to be remote from the main energy demand centres, long distance transportation may result with associated costs and environmental impacts.

The way forward is to transform biomass into energy in an efficient and environmentally friendly way, while reducing consumption and increasing energy efficiency. Food-based biofuels such as rape biodiesel can meet but a small portion of transportation energy needs. While feedstock availability is a barrier to rape biodiesel development, economic drivers are equally of critical importance. As irrigation for biodiesel production is rarely acceptable, biodiesel production should be favoured on lands wet enough to support substantial production but that are not serving other valuable needs ('degraded' lands). A genuinely sustainable biodiesel industry requires that the risks of indirect effects are significantly reduced by setting lower targets, by ensuring that feedstock production takes place on idle or marginal lands (*i.e.* lands of low competition), and/or by encouraging technologies that utilise noncrop-based feedstock (such as wastes or algae). These measures reduce pressure for land-use change. Also the energy balance (and possibly cost competitiveness) of biodiesel can be improved by use of low-input biomass, by-products (tallow) or waste products (cooking oils).

The future of biodiesel lies in the use of non-edible energy crops grown on degraded land or requiring no land-use. The availability of these feedstocks (jatropha, algae) is still limited. With time, the bioenergy situation will change dramatically once the production of cellulosic ethanol becomes commercially viable.

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